911 G-31

AN ASSESSMENT OF AERODYNAMICALLY AIR-STAGED COAL BURNER

Prepared by:

DATUM ENGINEERING LIMITED
Oakville, Ontario

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Canadian Electrical Association

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AN ASSESSMENT OF AERODYNAMICALLY AIR-STAGED COAL BURNER

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Prepared by:

R.J. Wreford, P. Eng.

DATUM ENGINEERING LIMITED
126 Talbot Drive
Oakville, Ontario
L6L 4C5

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EXECUTIVE SUMMARY

The International Flame Research Foundation (IFRF), IJmuiden, The Netherlands, has recently completed a research program on the development of a 2.5 MW_t aerodynamically air staged burner (AASB). The "semi-industrial scale" test burner is designed for pulverized coal combustion with low NO_x emission. The test data, results and discussion of this program are contained in eight research reports published by the IFRF. Canada, through the Canadian Electrical Association and EM&R, is a sponsor of the program and, as such, has access to this material.

In June, 1989, the CEA invited Datum Engineering, Oakville, Ontario, to review the collected reports for the purposes of:

(a) evaluating the reported performance of the AASB with particular regard to NO_x reduction potential, and

(b) assessing the feasibility of scaling up the burner to a prototype size of about 40 MW_t.

The CEA Technical Advisor for this study was Mr. I.D. Covill, P.Eng., of the Nova Scotia Power Corporation.

The AASB represents one of several low-NO_x burners studied recently at the IFRF. Like most of these, it employs the principle of air-staged combustion to delay fuel-air mixing at stoichoimetric conditions. Whereas other burners promote this delay by physical separation of the air streams, the AASB achieves the necessary separation by a somewhat delicate balance between the primary and secondary stream flow characteristics, such as velocity, direction and swirl. In other respects, the AASB design is relatively uncomplicated.

An outside, conical secondary air stream is imparted with just sufficient swirl to create a large central internal recirculation zone (IRZ) composed of oxygen-lean combustion products. For optimum NO_x reduction, the primary coal/air stream must possess just sufficient momentum to penetrate the IRZ, at which point primary pyrolysis takes place.

NO_x levels consistently in the range of 320 ppm. This is about 100 to 200 ppm lower than the in-service emission levels attained by current commercially available burners.

Carbon losses were generally not excessive. Early tests gave unacceptably low burnout (90%-98%), but investigation revealed a furnace gas path channelling which probably distorted the figures. In later tests, carbon burnout varied between 98 and 99 percent under optimum conditions.

Scale-up experience with other low-NO_x burners suggests that full-scale emission levels should be lower than those for the test unit.

The reports do not address the burner turn-down capabilites, but the 2.5 MW_t burner would not be capable of generating results that could be related to full scale operation in any case.

Manufacturers representatives were generally reluctant to undertake a detailed examination of the AASB. A preliminary review of the available report drawings identified no significant obstacles to the manufacture of a prototype AASB in the 40-60 MW_t range. Prerequisites would be a licencing agreement and some degree of funding of the engineering, design and fabrication program. One manufacturer estimated the total cost of this phase to be in the area of $500,000. Additional to this would be the cost of a test program on several coals, at a candidate utility.

SOMMAIRE

La Fondation internationale pour la recherche sur les flammes de foyer (International Flame Research Foundation - IFRF), sise à Ijmuiden, aux Pays-Bas, a récemment achevé un programme de mise au point d'un brûleur de 2,5 MW_t à configuration aérodynamiquement progressive (AASB). Le brûleur expérimental à l'échelle "semi-industrielle" est conçu pour la combustion de charbon pulvérisé avec faible dégagement de NO_x. Les donnés sur les essais, les résultats et l'analyse de ce programme sont regroupés dans huits rapports de recherche publiés par l'IFRF. Le Canada, par l'entremise de l'Association canadienne de l'électricité et le ministère EMR, fait partie des commanditaires du programme et, à ce titre, a droit d'accès à cette documentation.

En juin 1989, l'ACE invitait la firme Datum Engineering d'Oakville (Ontario) à passer en revue les rapports obtenus afin:

(a) d'évaluer la tenue observée de l'AASB en ce qui concerne le potentiel de réduction des NO_x;

(b) d'évaluer la faisabilité du passage à un prototype de brûleur de 40 MW_t environ.

Le conseiller technique de l'ACE, dans le cadre de ce projet, était monsieur I.D. Covill, ingénieur à Nova Scotia Power Corporation.

L'AASB represente l'un des nombreux brûleurs anti-NO_x étudiés récemment par l'IFRF. Comme la plupart d'entre eux, il fait appel au principe de la combustion progressive à l'air pour retarder le mélange combustible-air jusqu'à atteindre des conditions de stoechiométrie. Alors que les autres brûleurs provoquent ce retard par séparation effective des jets d'air, le brûleur AASB réalise cette séparation par un équilibre relativement délicat entre les caractéristiques d'ecoulements d'air primaire et secondaire, telles que la vitesse, la direction et la turbulence. Ceci dit, la conception de brûleur AASB est relativement peu complexe.

Un jet d'air secondaire conique, externe, est engendré avec juste assez de turbulence pour créer une vaste zone centrale de recirculation interne, composée de produits de combustion pauvres en oxygène. Pour obtenir une réduction maximale des NO_x, le jet primaire d'air-charbon doit posséder juste assez d'élan pour pénétrer dans la zone de recirculation, ce qui entraîne la pyrolyse primaire.

Lorsque ces conditions optimales sont réunies, le brûleur AASB est en mesure de réduire les émission de NOx de façon constante, à un niveau de 320 ppm, c'est-a-dire de 100 à 200 ppm plus bas que les émissions atteintes par les brûleurs actuellement commercialisés.

Les pertes de carbone se sont déclarées peu excessives. Des essais préliminaires ont donné des combustions inacceptables tant elles étaient faibles (90 à 98 %), mais une analyse des faits a révélé une canalisation du trajet des gaz dans le foyer, ce qui a probablement altéré les valeurs obtenues. Lors d'essais ultérieurs, la combustion du charbon variait de 98 à 99 % dans des conditions optimales.

Des expériences menées à plus grande échelle avec d'autres brûleurs anti-NO_x laissent penser que les niveaux d'émission en service réel devraient être inférieurs à ceux du modèle de brûleur à l'essai.

Les rapports ne traitent pas des capacités de débit moyen du brûleur, mais le brûleur de 2,5 MWt serait incapable de produire des résultats que l'on pourrait extrapoler à une exploitation à grande échelle, quel que soit le cas.

Les représentants des constructeurs se sont montrés en général réticents devant l'entreprise d'un examen détaillé du brûleur AASB. Une analyse préliminaire des schémas et plans contenus dans les rapports n'a relevé aucun obstacle important pour la fabrication d'un AASB prototype dans la gamme allant de 40 à 60 MW_t. Les exigences préalables porteraient sur l'octroi d'une licence et sur une certaine partie du financement du programme d'ingénierie, de conception et de fabrication. Un des constructeurs a évalué le coût global de cette phase à environ 500 000 $. Il faudrait ajouter à cela le coût d'un programme d'essai de plusieurs charbons et celui d'une entreprise d'électricité volontaire.

1.0 INTRODUCTION

In June, 1989, the Canadian Electrical Association authorized Datum Engineering Limited to undertake a review of the pulverized coal fired burner designated as the "Aerodynamically Air Staged Burner" (AASB), which has been developed at the International Flame Research Foundation in the Netherlands. The review was to be based on seven research reports issued by the IFRF, which described the development of the AASB and the extensive test program to evaluate its capabilities. A further report, Report No.8, was subsequently added as it provided material related to the potential "scale-up" of the burner. The research program, which also investigated several other pulverized coal burner arrangements, was devised specifically to develop NO_x-reduction techniques by means of flame temperature and stoichiometry control. The CEA Technical Advisor for the Datum Engineering study was Mr. I.D. Covill, P. Eng., of the Nova Scotia Power Corporation.

The objectives of the review by Datum Engineering were to:

(a) assess the results of the AASB trials with regard to its potential for NO_x reduction in an industrial or utility scale application, and

(b) investigate the practicality of commercial development in the 40 MW_t and larger size range.

The International Flame Research Foundation (IFRF) at IJmuiden, the Netherlands, has been involved in "semi-industrial scale" research in pulverized coal combustion systems for more than 10 years. The reduction of NO_x formation has been a principal objective, and various aspects of this problem have been investigated. The test furnace used has a heat release of about 2.5 MW_t, and physical dimensions scaled to simulate conditions in a typical industrial size water tube furnace.

In addition to much valuable research data on the chemistry of NO_x formation, the IFRF studies have produced three relatively successful low-NO_x burner designs. In the sequence of their development, these are the:

- Externally Air Staged Burner (EASB)

- Air Staged Precombustor Burner (ASPB)

- Aerodynamically Air Staged Burner (AASB)

Each of these employs different means of stoichiometric control to promote the release of fuel volatile matter in an oxygen-lean environment. Basic technical and performance descriptions of these burners are contained in Section 2.0.

Of the three burner types, the AASB most closely matches the external dimensions and quarl opening for a conventional pulverized coal burner. Both the EASB and ASPB require substantially more windbox space and/or additional water wall penetrations. Furthermore, preliminary tests of the AASB have indicated encouraging results in the reduction of NO_x levels for a range of coals.

Increasingly stringent NO_x emission regulations will almost certainly create the need for improvements to many existing utility combustion systems. Hence, it is envisioned that the AASB presents commercial opportunities in the potential retrofit market for existing utility and large industrial boilers.

1.1 Reference Reports

This review of the capabilities and potential of the AASB is based on the following IFRF reports, as provided to Datum Engineering by the Canadian Electrical Association.

	IFRF Doc. No.	Title	Authors
1.	F 037/a/16 Feb., 1987	NO_x Reduction With Coal Firing By Application of Both Internal and External Air Staging and Fuel Rich Precombustors (AP 14 Trials)	Weber Smart Phelan
2.	F 037/a/18 May, 1987	NO_x Reduction and Burnout Optimisation Using Aerodynamic Air Staging and Air Staged Precombustors (AP 16 Trials)	Smart Weber
3.	F 088/a/5 May, 1988	Evaluation of Residence Time and Temperature Distribution in IFRF Furnace Number 1 (CC 2-1 Investigation)	Smart Kimura Knill
4.	F 088/a/6 May, 1988	Effect of Coal Particle Size and Gun Design on NO_x Reduction Using an Aerodynamically Air Staged Burner (CC 2-2 Trials)	Knill Kimura Smart
5.	F 088/a/8 Nov., 1988	Detailed Characterization of the Near Burner Field of a Low NO_x Burner Firing Coal of Two Different Ranks (CC 2-4 Experiments)	Smart Knill
6.	F 088/a/9 Feb., 1989	Effect of Coal Quality on the Performance of Low NO_x Burners (CC 3 Investigation)	Morgan Dekker
7.	F 37/a/19 May, 1989	The Effect of Scale on the Performance of the Aerodynamically Air Staged Burner (AP 17 Experiments)	Smart Van de Kamp Morgan
8.	F 336/a/13	Computations of Near Burner Zone Properties of Swirling Pulverized Coal Flames (MMF 2 Investigation)	Visser Weber

Through the remainder of this report, reference studies will be identified by the above numerical sequence (1 - 8).

1.2 Research Development

The following simplified outline illustrates the sequential progression of this research as it developed over a period of about two years:

Report

#1	A comparison of the Precombustor Burner and the Internally Air Staged Burner (AASB)
#2	Further optimization of the operating conditions of each burner
#3	An evaluation of Furnace No.1 residence time and temperature profile to verify similitude with larger furnaces
#4	A study of the effect of particle size and trajectory patterns in the AASB
#5	Detailed in-flame measurements to verify theories on the mechanisms of NO_x suppression
#6	A comparison of AASB performance with coals of various volatilities and reactivities
#7	An attempt to quantify AASB potential improvements with increase in scale
#8	Development of mathematical modelling to enhance performance predictions for full-scale burners

1.3 Coals Used

With pulverized coal burners, the greatest proportion of NO_x originates as nitrogen in the fuel, and emerges in the initial devolatilization process. The effectiveness of air-staged combustion can be expected to vary with the volatile content of the coal. A wide range of coals was selected for testing in order to establish the AASB performance:

		Report Number						
Coal	Type	1	2	3	4	5	6	7
Scotts Branch	HVB	X	X	X	X	X		
Heinrich Rob't	MVB	X	X					
Peak Downs	LVB					X		
Hugo	MVB						X	
Coal Valley	HVB						X	X
Rhein Braun	LIG						X	

In addition, correlation was made with other coals previously tested with the EASB.

1.4 Experimental Methods

Recognition is due the authors of these referenced works for the many innovative experimental techniques and measurement systems devised to gather and analyze the necessary data. In a brief performance-related review such as this study, these aspects are, by necessity, substantially understated.

2.0 BURNER DESCRIPTIONS

2.1 General

The three low-NO_x burners developed at the IFRF are:

1. Externally Air Staged Burner (EASB)

2. Air Staged Precombustor Burner (ASPB)

3. Aerodynamically Air Staged Burner (AASB)

In basic principle, these are shown in Figure 2.1 (Report #1). The AASB is actually a re-classification of the earlier "Internal Air Staged Burner".

The EASB was first developed as a commercial design by Steinmuller GmbH, and was subsequently tested at the 2.5 MW_t scale at the IFRF. There appears to be some inconsistency among the reports as to the exact configuration of the Steinmuller design, but the basic principle of segregation of the sub-stoichiometric primary air/fuel mixture was established. The burner arrangement is shown on Figure 1.1 (Report #7).

Coal and primary air are discharged into the burner through a centre gun, while swirled secondary air is introduced around the circumference of the quarl. Tertiary air is injected through a number of smaller ports outside the quarl exit. Although references are made to EASB performance, the EASB was not tested in any of the trials reviewed for this report.

The two later burner designs evolved with impetus from other related research and development at the IFRF. These programs included, for example, near burner field aerodynamics, characterization of coal combustion performances, and the composition and release rates of volatile matter from pulverized coals as measured in the Isothermal Plug Flow Reactor.

2.2 Air Staged Precombustor Burner

This burner (Report #1, Fig. 8.1) employs physical separation of the primary coal/air stream within a refractory lined precombustor chamber. Tertiary air is introduced just inside the quarl exit. In the early experiments (Reports 1 & 2), the ASPB was evaluated in a number of arrangements. Variation of the combustion chamber length was effected by removal or addition of refractory sections. Air distribution parameters were adjusted over substantial ranges:

		Min.	Max.	Approx. Optimum
Primary Air:	Temp. (°C)	20	100	70
	Veloc. (m/s)	20	70	38
	Flow (kg/h)	250	550	250/300
Secondary Air:	Temp. (°C)	170	360	250
	Veloc. (m/s)	18	115	45
	Flow (kg/h)	372	2710	500/900
Tertiary Air:	Temp. (°C)	290	430	350
	Veloc. (m/s)	21	115	100
	Flow (kg/h)	412	2255	1500/2200

Primary to secondary air velocity ratios were varied to study their effect on the stability of the Internal Recirculation Zone (IRZ). Swirl level of the secondary air was also varied for this reason. Precombustor length was adjusted to alter the particle residence time. The formation of fuel NO_x was expected to be minimized by prolonging the residence time.

2.3 Aerodynamically Air Staged Burner

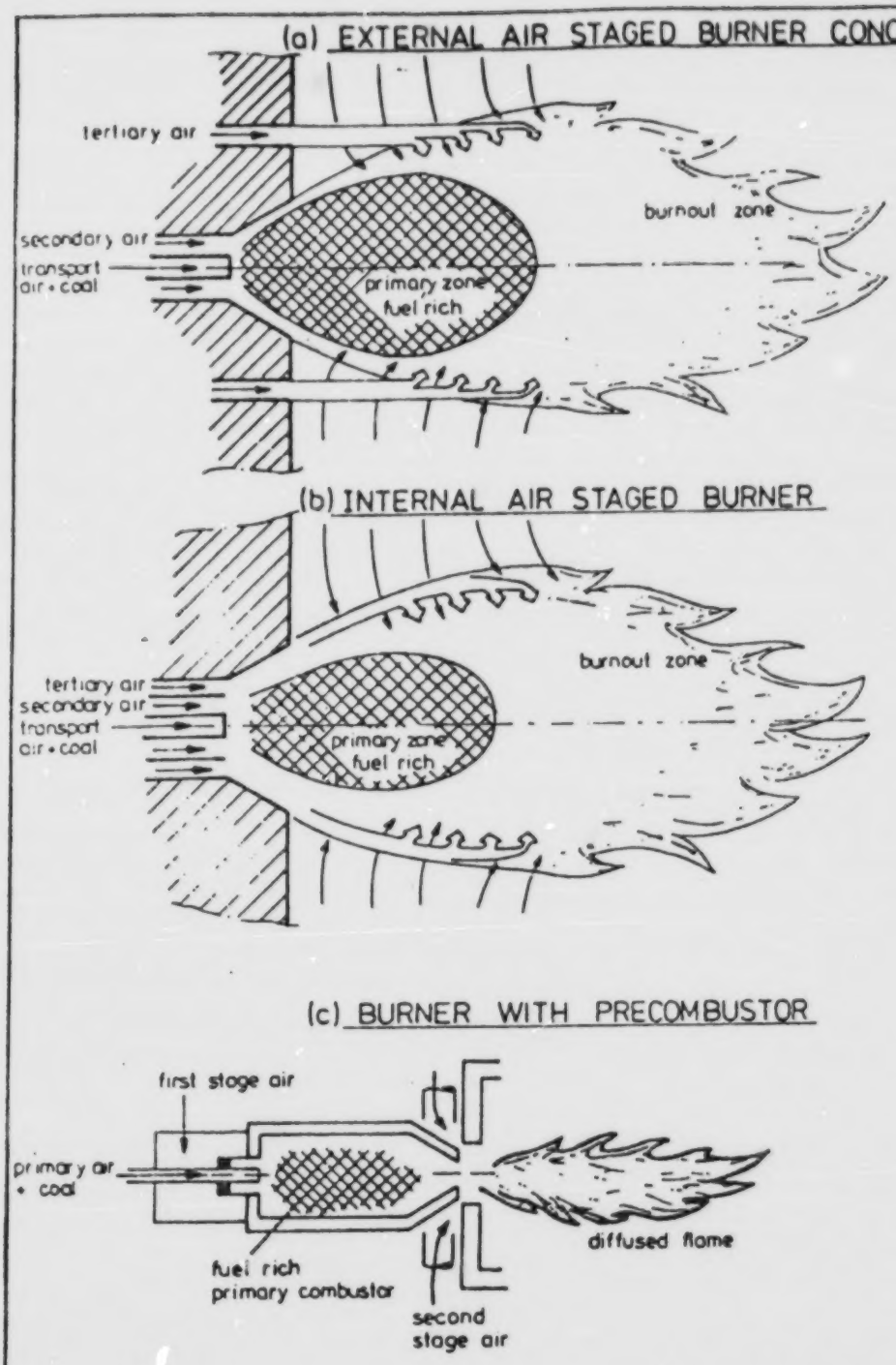
In early reports, this burner was identified as the internally air staged burner, and is shown in elementary form in Figure 6.2 (Report #1). With this version, a number of coal injector guns were tested to determine the effects of nozzle tip separation of the primary air stream from the secondary air or, as in the case shown, from the core air. The physical separation of these air streams by a nozzle insert or thick-walled injector gun (Figs. 6.3, 6.5, Report #1) proved to have very limited effect on the overall performance, and this concept was not pursued in later testing.

In principle, the AASB uses a conical form, high velocity, partially swirled secondary air stream surrounding a lower velocity, plug flow primary air and coal jet. The high velocity diverging secondary air flow creates something of a conical diffusor effect. In an expanding diffusor section, momentum energy is converted to pressure, thus generating an adverse (increasing) pressure gradient. It appears to be this pressure gradient which causes the formation of a central region of reversed flow, known as the internal recirculation zone (IRZ).

The recirculation zone is composed mainly of hot products of combustion, which are oxygen-lean. The release of nitrogen-containing volatile matter within this zone favours the formation of N_2 rather than NO_x. The combustion chemistry aspects of nitrogen conversion are discussed at length in Reports No. 2, 5 and 6. The IRZ thus provides an ideal environment for the primary pyrolysis stage of low-NO_x combustion.

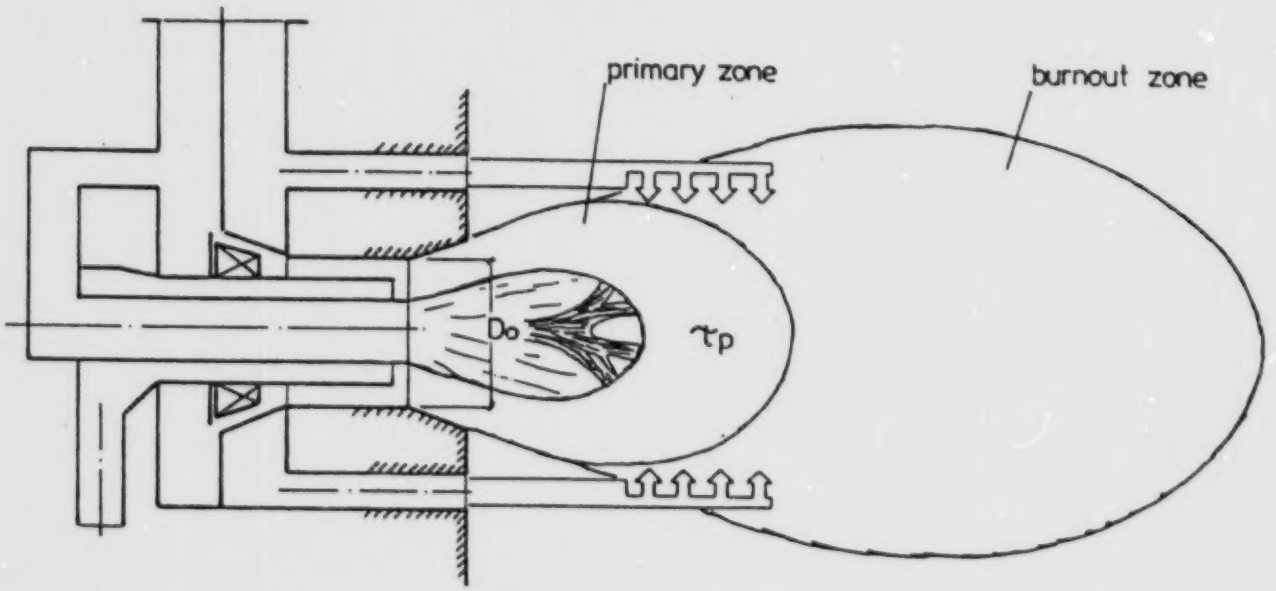
Generally, the AASB was fired with about 15 percent overall excess air. Primary air was injected at 300 or 500 kg/h, representing 12 or 20 percent of the required combustion air. It was preheated to, typically, 70° C. Secondary air was usually heated to 280 - 320°C. Various PA/SA velocity ratios and degrees of secondary air swirl were tried, in successive trials, in order to concentrate the IRZ.

The most significant feature of the AASB is the ability to adjust the position of the coal injector axially within the burner quarl. Early in the test program it was recognized that the position of the injector tip, relative to the burner throat, had a noticeable effect in reducing the furnace outlet NO_x level. The optimum extension was found to be about 0.6 quarl diameters from the throat station. From this point, the primary air/coal particle momentum could effectively penetrate the IRZ, resulting in substantial devolatilization within the oxygen-lean atmosphere.



IFRF

Fig. 2.1 : Some low NOx burner concepts



Q = burner thermal input
Do = characteristic burner diameter
τp = primary zone residence time

$\tau_p \sim \sqrt{\dot{Q}}$
$D_o \sim \sqrt{\dot{Q}}$

IFRF

Fig. 1.1 : Schematic of Steinmuller EASB

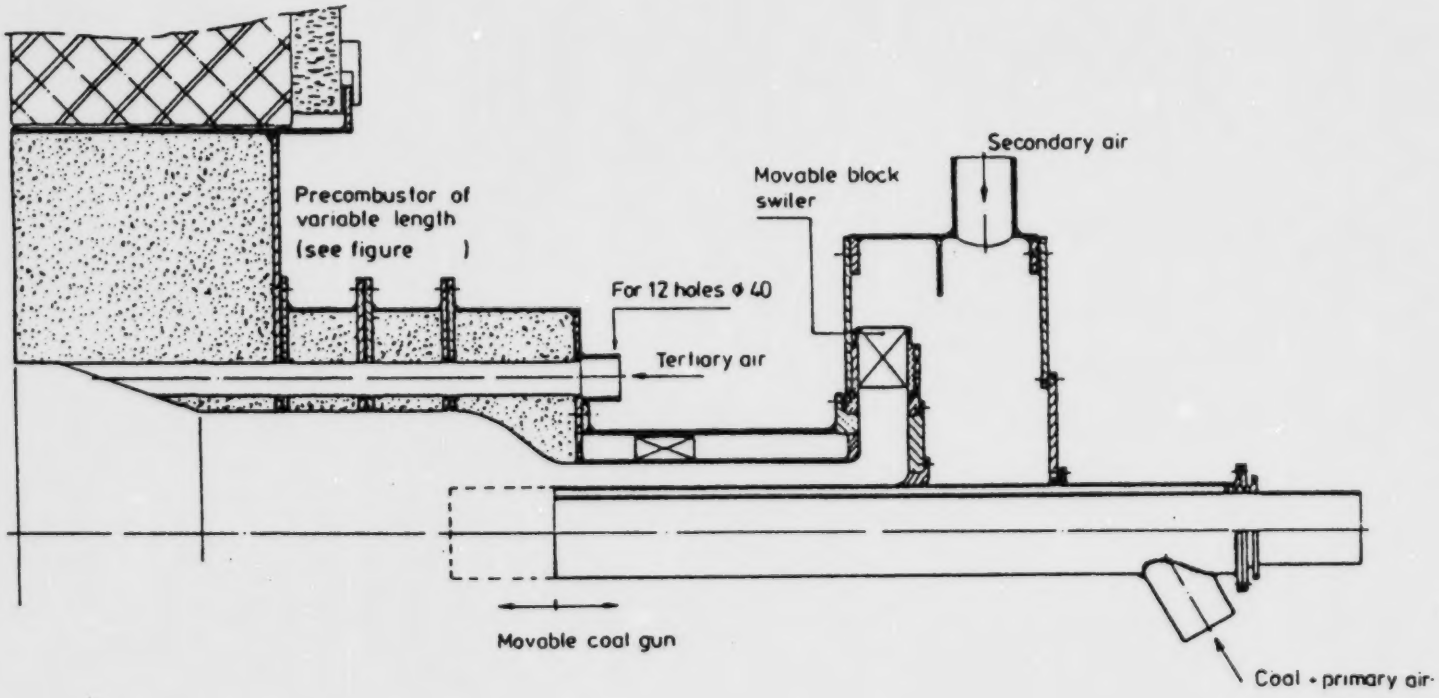


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Fig. 8.1 : AP - 14 burner nr. 3.

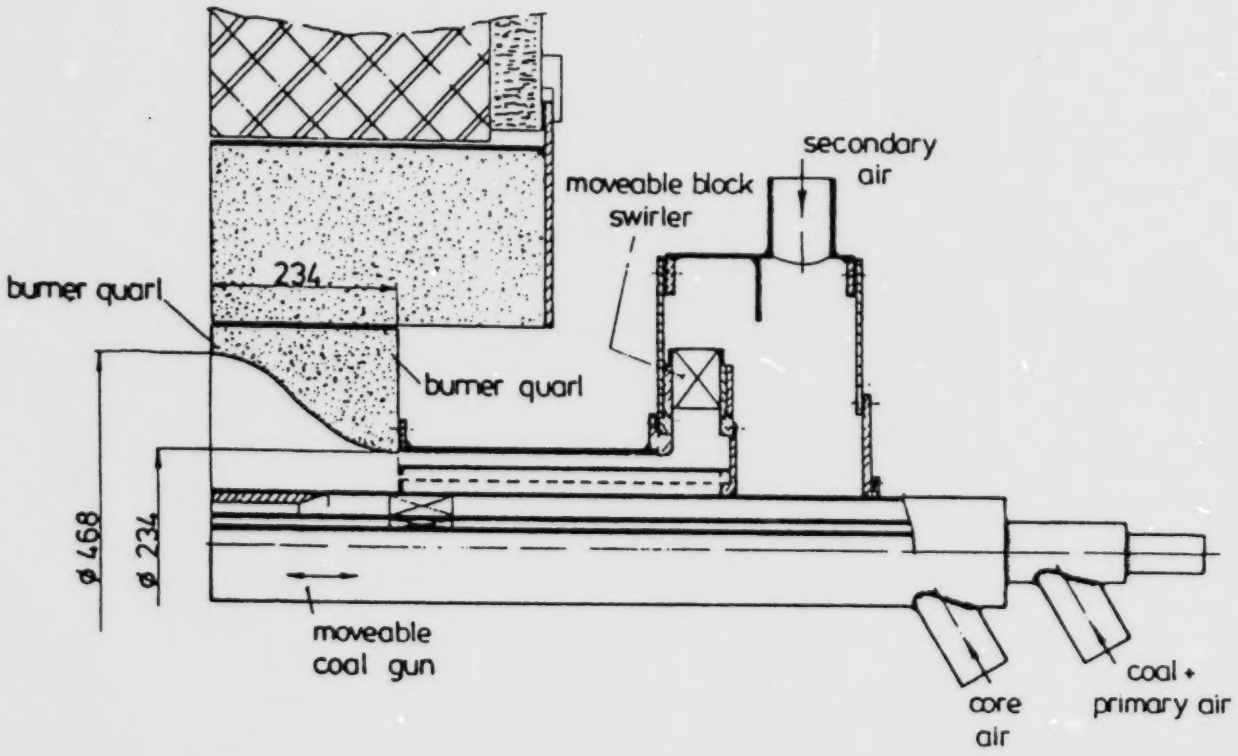

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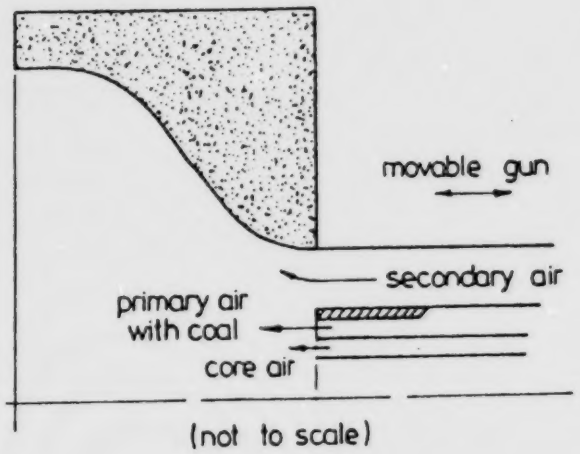
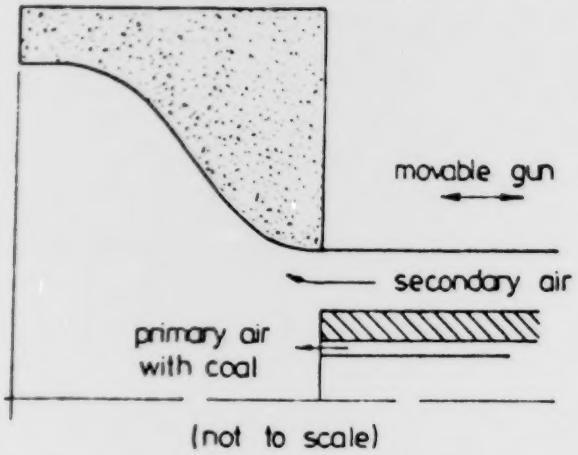
Fig. 6.2 : AP-14 internal air staging burner nr. 1.



Air	fraction of stoich. air	velocity m/s	temp. °C
secondary	1.1 - 0.84	33-25	~300
primary	0.212	42	80
core	0 - 0.247	0-90	~250

IFRF

Fig. 6.3 : Burner nr. 1 - Arrangement A



Air	fraction of staich. air	velocity m/s	temp. °C
secondary	1.09 - 0.99	38 - 37	~300
primary	0.11 - 0.21	27 - 54	~75

IFRF

Fig. 6.5 : Burner nr. 1 - Arrangement C

3.0 REVIEW OF REFERENCE REPORTS

The following section contains a review and summary of each of the reference reports related to the Aerodynamically Air Staged Burner. The reviews are intended to identify the principal results achieved, and to examine the conclusions drawn. It is not the objective, here, to reiterate the several interesting discussions of the important chemical reactions involved in NO_x formation, or to dwell on the experimental methods employed. For these topics, reference should be made to the original reports. For convenience, the illustrations referenced in each report are contained within that section.

3.0 REPORT NO 1

NO_x REDUCTION WITH COAL FIRING BY APPLICATION OF BOTH INTERNAL AIR STAGING AND FUEL RICH PRECOMBUSTORS Report on the AP 14 Trials

1.0 OVERVIEW

One of the most effective ways of reducing NO_x formation is the use of sub-stoichiometric techniques. Combustion takes place in a fuel rich environment with the remaining air introduced away from the combustion zone. This method lowers the burner zone flame temperature and limits the amount of nitrogen in the combustion air that can be converted to thermal NO_x, while controlling the devolatilization rate which restricts the availability of fuel nitrogen.

1.1 External Air Staged Concept

As can be seen from Figure 2.1(a)(following page 11, this report), primary (transport) and secondary air are introduced through the burner quarl, causing a primary zone fuel rich area. Tertiary air, necessary to complete the combustion process, is admitted into a lower temperature burnout zone. Thus, by reducing the available oxygen in the burner zone, the fuel-bound nitrogen will not be too readily converted to NO_x.

While an externally staged burner is capable of reduced NO_x formation for utility and industrial applications, its disadvantage lies in the costly retrofitting work necessary to re-design the windbox, burner zone and water wall assemblies.

1.2 Internal Air Staged Burner

The concept of this burner is the same as the External Air Staged version, that is, a sub-stoichiometric primary zone with final (tertiary) air supplied from within the burner quarl. It can be readily seen that this type of burner design is less costly to retrofit as major combustion chamber modifications are avoided.

1.3 Burner With Precombustor

The precombustor burner is essentially a combination of the external and internal air staged burners, in which the primary flame zone is maintained under fuel-rich conditions. While not as attractive to retrofit as the internal air staged burner, the perceived advantage of the precombustor burner is the ease of access and lower maintenance costs.

2.0 OBJECTIVES

The overall objective for the AP14 Trial was to conduct a "screening test" of the performance of three types of burners for potential NO_x reduction and carbon burn-out capability:

- A internal air staged burner with facility to physically separate primary and secondary air flows.
- An internal air staged burner with a deep quarl.
- A precombustor burner with a deep quarl of adjustable length.

3.0 TEST PROCEDURE

3.1 Furnace

Burner tests were carried out in IFRF Furnace No.1, a rectangular-section horizontal furnace arranged to simulate the radiant zone of a large water tube boiler. The furnace is refractory lined with internal dimensions approximately 2m x 2m x 6.25m length. The furnace is equipped with seven double water cooled loops spaced equally on 0.8 m centres along the axial length. This allowed for an average heat extraction of 50 percent from the total heat input of 2.5 MW_t. The mean flue gas exit temperature was 980°C. Heat extraction by the cooling loops was determined from flow measurements and temperature rise.

Two coals were used; Scotts Branch and Heinrich Roberts. The coals were pulverized to standard size, i.e. 75 percent by weight less than 75 microns. Fuel analyses are provided in Table 1 of the Report.

In Phase 1, three coal guns were systematically investigated for the short precombustor cases burner configuration A, Figure 8.2. It was believed that by optimizing the mixing in the primary, fuel-rich zone and/or splitting the coal stream into concentrated jets, NO_x emission levels could be reduced (flames 1-43 inclusive Table 8).

Phase 2 was concerned with the effect of residence time of coal in the fuel rich precombustor on NO_x reduction by means of varying precombustor length, coal gun position and primary zone stoichiometry (flames 44-61 incl., table 8).

The complete flame matrix for burner No. 3 is shown in Table 8. Table 9 shows detailed in-flame measurements for the selected flames.

Burner No. 3 employed a precombustor of variable length in which a well defined fuel-rich primary zone was maintained. Four configurations for the burner were tested and these differed in the length of the precombustor only.

3.2 Instrumentation and Measurement Techniques

The following list shows the instruments and measuring methods used:-

1. Gas temperature - suction pyrometers using Pt/Pt Rh (10%) thermocouples
2. Oxygen - paramagnetic analyser
3. Carbon Dioxide - infra red analyser
4. Carbon Monoxide - infra red analyser
5. NO_x - chemiluminescence analyser
6. Particulate Matter - water cooled probe with ceramic filter
7. Acetylene probe - this equipment comprises a water cooled tip, which carries a small premixed air/acetylene flame. This flame acts as a "flag", indicating the direction of furnace flow streams. With this information the internal and external recirculation zone and furnace exit can be mapped at low stream velocities.

3.3 Internal Air Staged Burner No.1

Two internal air staged burners were investigated in Report #1, denoted by burners #1 and #2.

For Burner #1, three variations were studied as shown in Figures 6.3, 6.4 and 6.5.

Arrangement "A" comprised core air, transport air and secondary air with a moveable gun. The three air supplies had specific percentages of stoichiometric, velocities and temperatures.

Arrangement "B" is the same as 6.3 but without core air. The primary and secondary airs had differing values for stoichiometric air, velocity and temperatures. The gun was also moveable.

Arrangement "C" has no core air and again different ratios for the primary and secondary stoichiometric, velocity and temperature.

In all, 24 burn tests were carried out, 14 using Scott's Branch coal and 10 using Heinrich Roberts. The burner arrangements were:

1 - 5	Burner Arrangement	A.	Scott's Branch
6 - 10	"	B.	"
11 - 14	"	C.	"
15 - 24	"	C.	Heinrich Roberts

3.4 Internal Air Staged Burner No. 2

The original concept for this burner and the experimental version are shown in Figures 7.1 and 7.2 respectively. The expected flow pattern was an internal recirculating zone within the diverging section of the quarl, followed by a second internal recirculating zone, with good fuel and air mixing in both zones. The objective of the tests for #2 burner was to optimize input parameters to produce minimal NO_x emissions. It should be noted that due to space limitations of this burner design, there were some constraints in varying some of the input parameters.

3.5 Precombustor Burner No.3

The experimental version of Burner #3 is shown in Figure 8.1. The burner incorporated a precombustor 0.3 m in diameter with four variable lengths in the range 0.27 m to 0.97 m, as shown in Figure 8.2, which was designed to produce a cylindrical flow (parallel to the precombustor walls) of the secondary air.

Staged air was supplied through either six or twelve ports uniformly distributed in the second quarl at the precombustor exit. For this series of tests five different coal guns were used.

Objectives of this test were:

1. To assess the NO_x reduction capability and carbon conversion efficiency under different operating condition.

2. To assess the performance of several coal guns particularly when these were combined with the short precombustor.

3. To monitor the process of slagging of the precombustor walls, particularly for the longest precombustor configuration.

The experimental programme was performed in two phases. In the first phase, the five guns were investigated for a short quarl length of 0.27 m as shown in configuration A, Figure 8.2. The results are contained in flame tests 1-43, Table 8.

Phase 2 was concerned with the effect of residence time of the coal in the fuel-rich combustor on NO_x reduction. Residence time was adjusted by varying the precombustor length. These results are contained under flame tests 44-61, Table 8.

4.0 SYNOPSIS OF TEST RESULTS

4.1 Burner No. 1 Results

By optimization of the input aerodynamic parameters of the burner, a relatively large internal recirculation zone (IRZ) can be obtained. When the coal gun was then inserted into the IRZ and the primary air momentum was decreased, short flames were obtained on Scott's Branch

coal. Flue NO_x emission in the range 320-370 ppm (0% O_2) and good carbon burnout of 96-98% was obtained with this arrangement.

It was also found that when the coal gun was inserted inside the burner quarl, in order to maintain a fuel-rich environment in the IRZ and, therefore, obtain substantial NO_x reduction, the primary air flow rate ought to be decreased.

Long jet-like flames were also obtainable on burner #1. However, these flames gave low NO_x emission only in the case when there was no core air (see burner configuration "C") and the mixing between the primary and secondary air streams was delayed by means of the physical separation of primary and secondary streams at the quarl inlet.

4.2 Burner No. 2 Results

There were ten tests carried out which are shown in Table 6 of the report. The maximum and minimum values for NO_x at 0% O_2 are 840 ppm (Test #7) and 495 ppm (Test #1) at 0% O_2.

In general NO_x levels were high, nine of the ten tests being in the range 553 ppm to 840 ppm. Attempts to reduce NO_x levels by varying input parameters including burner geometry proved unsuccessful.

4.3 Burner No. 3 Results

The precombustor burner results were not published in the main body of the report, but the data is presented in Tables 8 through 13.

5.0 REPORT CONCLUSIONS

1. Burner #1, when burning Scott's Branch coal and internally air staged combustion produced 320 ppm NO_x (0% O_2) with a char burnout of 96%. This is flame Test #8. Other tests i.e. 9-12 inclusive also using Scott's Branch coal, are encouraging.

2. Burner #2 tests have to be regarded as unsuccessful, due to the high NO_x levels that were obtained.

3. The results of burner #3 indicate that low NO_x figures can be obtained for configuration "A", Figure 8.2, but at the expense of poor char burnout.

4. As the precombustor length increases, i.e. increased residence time, there are improvements in char burnout but no corresponding reductions in NO_x concentrations, with the exception of two flame tests at 0.97m (configuration "D").

6.0 COMMENTARY

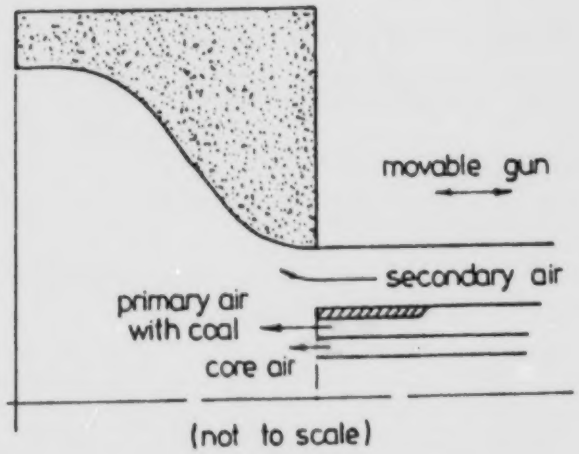
The development of sub-stoichiometric techniques is an effective way of reducing NO_x formation, since it lowers the flame temperature and reduces the nitrogen in the combustion air that can be converted to thermal NO_x, while controlling the devolatilization rate which regulates the availability of fuel nitrogen.

Burner #1 concept was attractive since it produced a NO_x level of 320 ppm at 0% O_2. This should be considered for further investigation.

Burner No.2 yielded high NO_x values, and poor carbon burnout and, therefore, was considered unsuccessful.

Assuming a typical pulverized coal furnace operating at 4% excess oxygen, a NO_x value of around 250 ppm could be obtained. The NO_x value of 320 ppm would not be significantly reduced on an oil fired unit, where excess oxygen levels are typically 0.5 percent.

The precombustor, or Burner No. 3, is really a combination of internal and external concepts, in which the primary zone operates at fuel rich conditions. The advantage of this design would appear to be for new units only, since retrofitting to existing units could lead to expensive modifications and long downtimes. Furthermore, many existing units would be faced with space limitations preventing retrofit of this burner. The report fails to explain the purpose of the core air used with Burner #1. This is particularly relevant in view of the encouraging NO_x figures obtained.



Air	fraction of stoich. air	velocity m/s	temp. °C
secondary	1.1 - 0.84	33-25	~300
primary	0.212	42	80
core	0 - 0.247	0-90	~250

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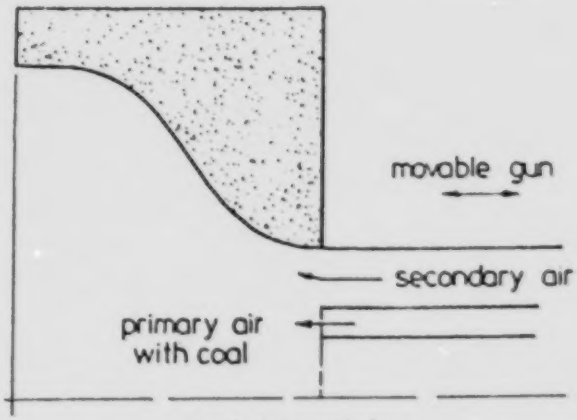
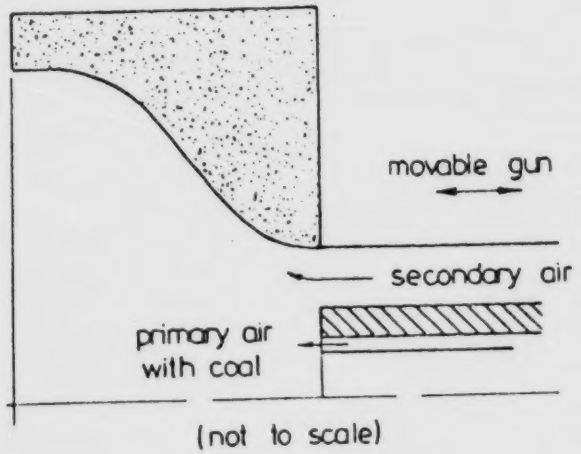
Fig. 6.3 : Burner nr. 1 - Arrangement A



Air	fraction of stoich. air	velocity m/s	temp °C
secondary	1.03 - 0.988	35 - 31	~280
primary	0.17 - 0.212	62 - 13	~80

IFRF

Fig. 6.4 : Burner nr. 1 - Arrangement B



Air	fraction of stoich. air	velocity m/s	temp. °C
secondary	1.09 - 0.99	38 - 37	~ 300
primary	0.11 - 0.21	27 - 54	~ 75

IFRF

Fig. 6.5 : Burner nr. 1 - Arrangement C

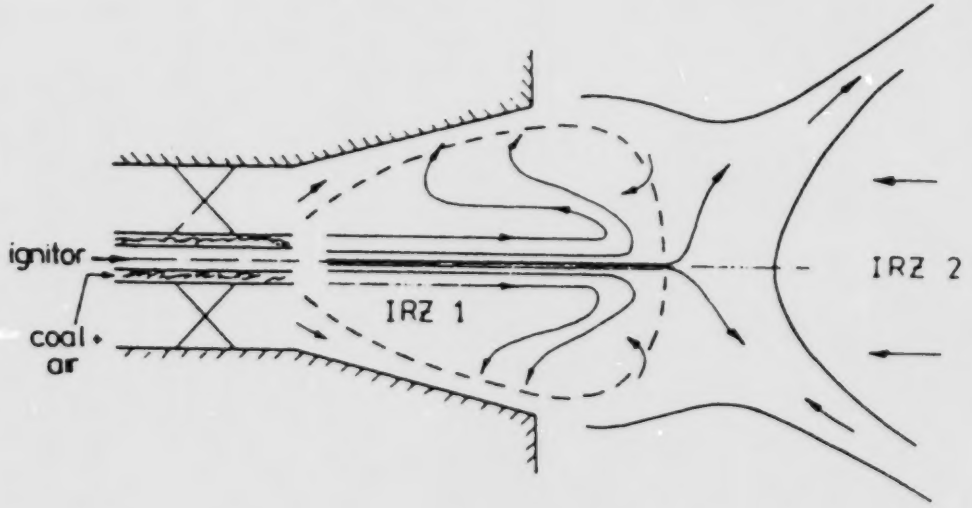


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Fig. 7.1: Orginal concept for burner nr. 2
- the type 3 flame approach -

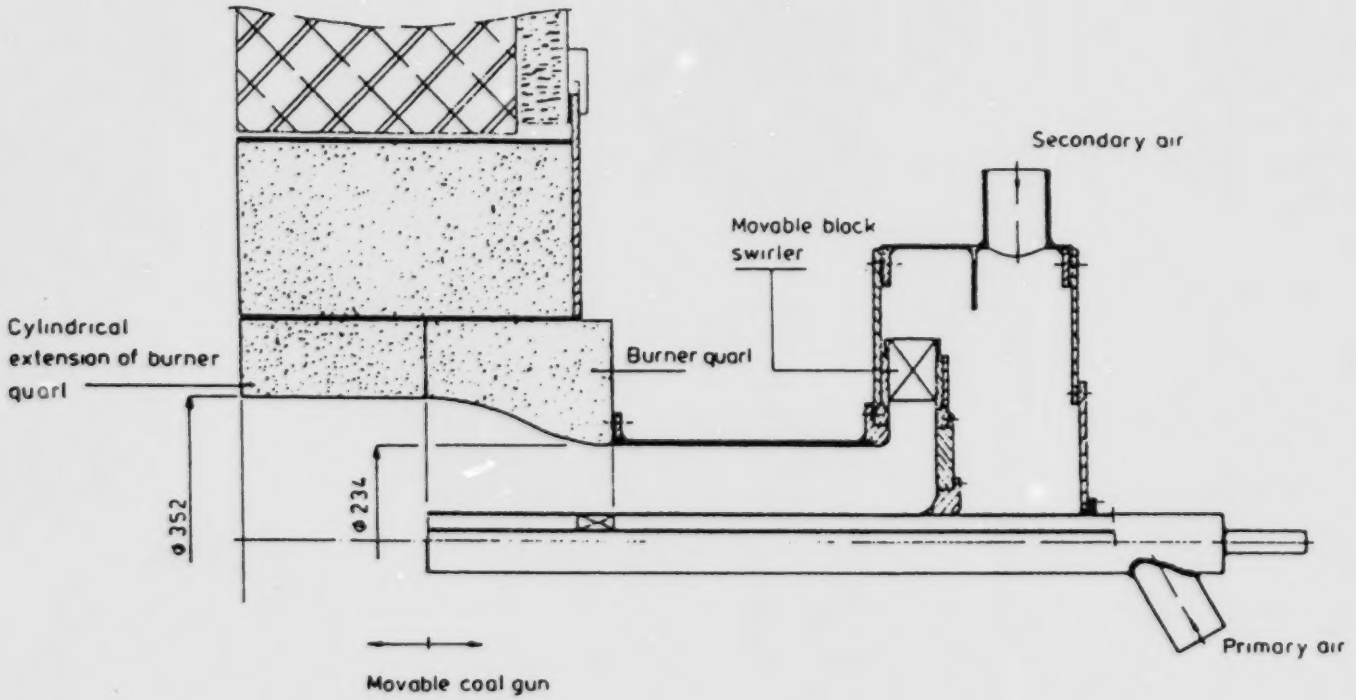

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Fig.7.2 : AP-14 burner nr. 2.

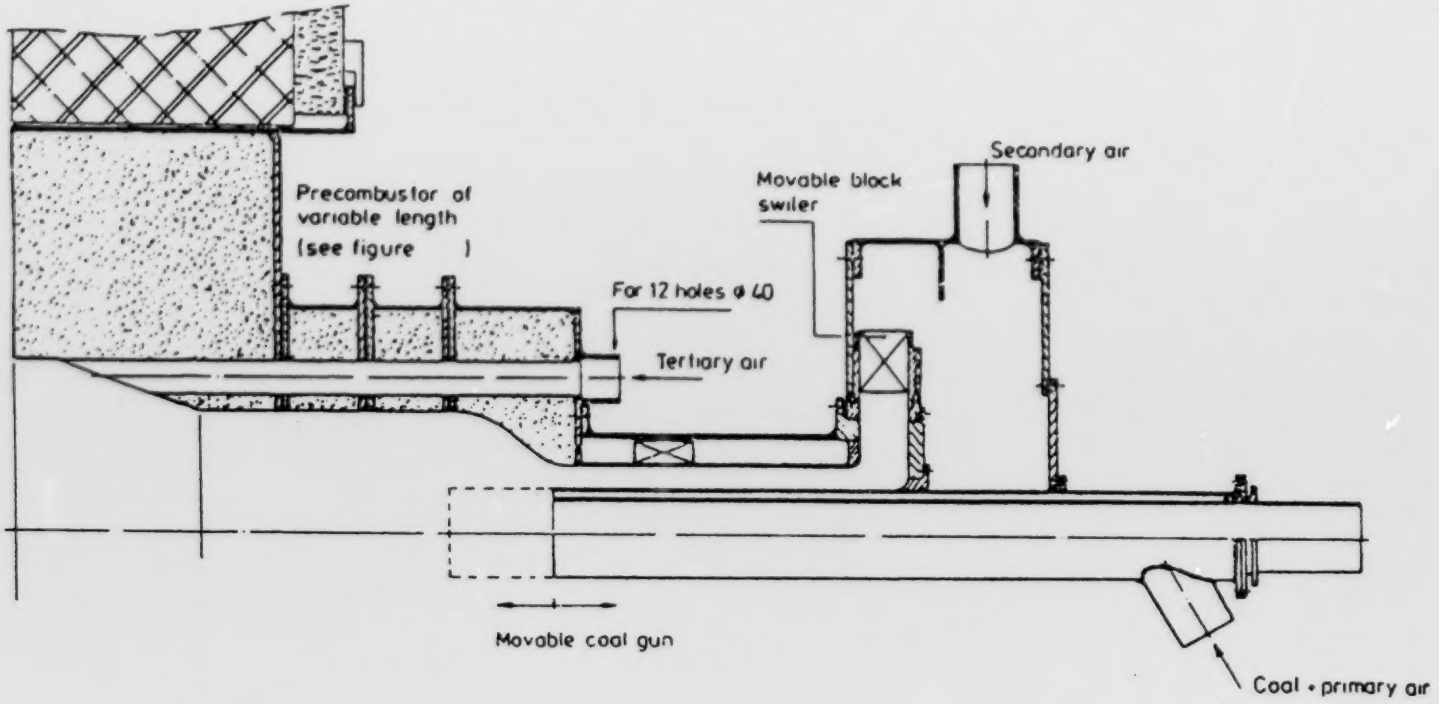

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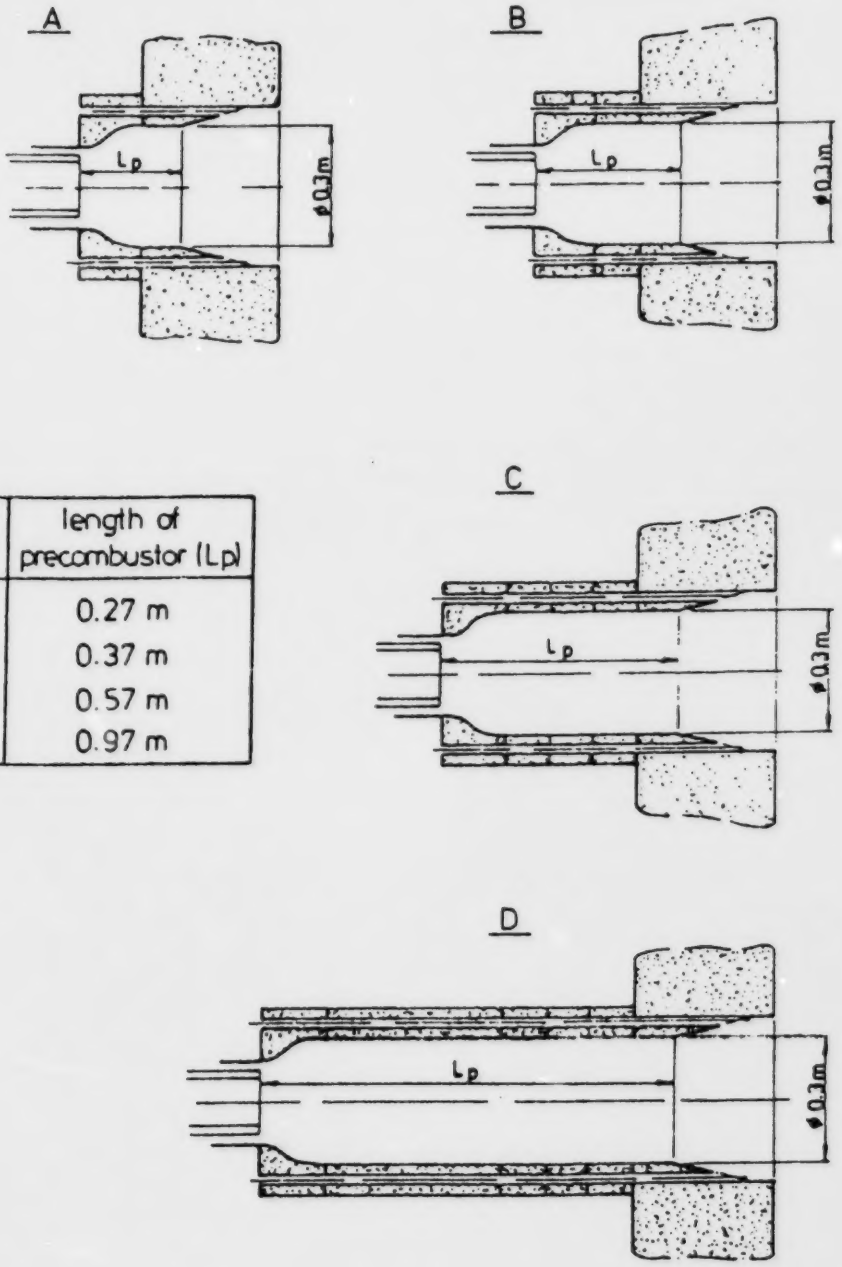
Fig. 8.1 : AP - 14 burner nr. 3.



configuration	length of precombustor (Lp)
A	0.27 m
B	0.37 m
C	0.57 m
D	0.97 m

IFRF

Fig.8.2 : Four configurations of the experimental burner nr. 3

3.0 REPORT NO. 2

NO_x REDUCTION AND BURNOUT OPTIMISATION USING AERODYNAMIC AIR STAGING AND AIR STAGED PRECOMBUSTORS Report on the AP 16 Trials

1.0 OVERVIEW

1.1 Previous Work Report No.1

In research, three different internally air staged burners were evaluated. The results showed that Report #1, burner #1 gave NO_x emissions of 320 ppm at 0% O_2, with a carbon burn-out of 98%. The second burner, Report #1 burner #3, which incorporated a precombustor gave NO_x emissions of about 340 ppm at 0% O_2. The Report #2 test program was carried out to extend and complement the data generated in Report #1, burners #1 and #3 results. Burner #2 was not successful.

1.2 Aerodynamically Air Staged Burner (AASB)

A schematic of the aerodynamically air staged burner is given in Figure 3.2.

Optimizing the interaction between the coal jet and the internal recirculation zone forms the basis of the design strategy for this burner. The optimized design can be considered as that which promotes initial devolatilization and combustion of the coal within the internal recirculation zone.

The burner quarl had a length to diameter ratio (L/A) of 1.0, a quarl expansion ration (B/A) of 2.0 and a zero inlet and outlet angle. The quarl profile was designed to fit a third order polynominal subject to these boundary conditions (Figure 3.3).

For each gun the following burner input parameters were investigated:

- Coal injector position
- Primary/secondary air velocity ratios
- Swirl level

1.3 Air Staged Precombustor Burner (ASPB)

A schematic of the air staged precombustor is given in Figure 3.6. This burner employs a precombustor in which a well-defined fuel-rich primary zone may be maintained within the precombustor chamber at a relatively high temperature.

The burner quarl had a length-to-diameter ratio of 1.0, a B/A ratio of 2.0 with a zero inlet and outlet angle. In this burner, the following were investigated:

- Primary/secondary velocity ratios
- Swirl level
- Precombustor response time
- Precombustor stoichiometry

2.0 OBJECTIVES

The objectives were:

1. To perform a series of detailed parametric studies using two flexible experimental burner designs based on burner #1 and #3 from Report #1.
2. To fire each burner with the same high volatile bituminous coal fired in Report #1 (Scotts Branch).
3. To fire each burner with the same medium volatile bituminous coal fired in Report #1 (Heinrich Robert).
4. To fire each burner with a 50/50 blend of the high volatile bituminous and medium volatile bituminous coals.
5. To perform a series of detailed in-flame measurements on selected flames in order to gain an insight into the NO_x formation/destruction mechanism under actual coal firing condition.
6. To generate NO_x burnout correlations for each burner/coal combination.

3.0 TEST PROCEDURE

3.1 Coal Selection

Two coals were used for the test programme: Scotts Branch high volatile bituminous and Heinrich Robert medium volatile bituminous. Each coal was transported to the burner at a nominal air/fuel ratio of 2.0. Burner thermal inputs were set nominally at 2.5 MW.

3.2 Combustion Air

Primary air at $70^{o}C$ at the burner comprised between 12% and 20% of the stoichiometric air requirement. Combustion air had a nominal temperature of $300^{o}C$. Primary and secondary air velocities were varied. A nominal excess air level of 15% was used for all tests.

3.3 Instrumentation

NO_x	-	Water cooled probe and a chemiluminescent analyser.
O_2	-	Water cooled probe and a paramagnetic analyser.
CO_2	-	Water cooled probe and an infra-red analyser.
CO	-	Water cooled probe and an infra-red analyser.
HCN/CH_3	-	IFRF CYAM technique.
Temperature	-	Suction pyrometer with P_t - P_t/R_h (10%) thermocouple.
In-flame flow	-	Acetylene probe profile.
Gas/solid (in-flame)	-	IFRF B-probe (bronze filter).
Gas/solid (in-flue)	-	IFRF Alcan-probe (bronze filter).

4.0 SYNOPSIS OF TEST RESULTS

4.1 Aerodynamically Air Staged Burner - General

In these results, burner input parameters such as swirl intensity, vortex type, primary/secondary velocity ratios, coal injector position and coal jet momentum were the controlled variables..

Also, taken into account were the properties of each coal in terms of devolatilization rate, maximum volatile yield and, most important, the distribution of coal bound nitrogen species between the volatile matter and char temperature. A final consideration was that the devolatilized nitrogen species was maintained within the confines of the internal recirculation zone for as long as possible to optimise decomposition to molecular nitrogen.

4.2 Scotts Branch High Volatile Bituminous Coal

The flame matrix for Scotts Branch coal is given in Table 2 of the report, which comprises of 96 flame numbers under varying penemetric conditions. These are commented on as follows:

4.2.1 Effect of Coal Injection Position - Gun A, Annular Coal Injector

The effect of coal injector position on flue NO_x emissions is shown in Figure 4.1. Generally it can be seen that injector insertion results in a significant drop in NO_x. However, some results show that with the coal injector

situated between -50 mm and 0 mm (within the burner throat), it can be seen that flue NO_x emissions are generally high and very sensitive to initial mixing levels.

Figure 4.1 also illustrates that when the coal injector is inserted beyond 0 mm, the sensitivity of the flue NO_x emissions to initial mixing intensity is much reduced. On inserting the coal injector more than about +175 mm, NO_x increases slightly.

Optimized NO_x emissions are in the region of 330 ppm at 0% O_2. Figure 4.2 shows no correlation between gun position and carbon burnout.

4.2.2 Effect of Swirl Level - Gun A, Annular Coal Injector

The effect of swirl level on NO_x emissions for the annular gun injector is shown in Figure 4.4. The trends clearly indicate that reducing swirl can reduce the flue NO_x emissions for all injector positions and primary/secondary air velocity ratios investigated.

This observation is explained, since the burner was designed with the objective of maximising devolatilization within the fuel-rich IRZ. This leads to optimum NO_x reduction conditions.

4.2.3 Effect of Primary/Secondary Velocity Ratio - Gun A, Annular Coal Injector

With the aerodynamically air staged burner, it was possible to generate all flame types cited in previous IFRF documents by varying the primary to secondary velocity ratios.

Type 0 Flames

These jet flame types are characterised by having no internal recirculation zone and were observed for input swirl levels less that 0.6. It should be noted that these swirled jet type flames still expand in the burner quarl, but their initial internal pressure distribution is insufficient to generate an IRZ. The type 0 flames studied also show the characteristic reduction in NO_x with coal injector insertion, but in this case, low NO_x is attributable to the delayed mixing between the coal jet and the secondary air. Jet flames tend to have a relatively high burnout due to maintaining high temperatures for longer in the furnace.

Type I Flames

These flame types are defined as those having coal jets with sufficient momentum to penetrate the internal recirculation zone. In these experiments, these flame types were generated with a primary air velocity of circa 77 m/s, and the coal injector inserted more than +50 mm. When complete penetration occurs, NO_x emissions increase as can be seen in Photographs 2, 3, 4 and Figure 4.1. One problem is that type I flames can be unacceptably long.

Type II Flames

Type II flames were formed when swirl levels were greater than 0.6, and the primary/secondary air velocity ratios were between 0.42 and 1.05. In this case, the coal jet does not completely penetrate the internal recirculation zone. Type II flames appear to fall into two categories; the "attached" type II where the flame completely "fills" the quarl; and the "unattached" type II where a clearly visible gap between the flame boundary and the quarl is observed. Inserting the coal injector beyond +100 mm will also result in an "unattached" flame. For both type II flame conditions, gun insertion causes a reduction in NO_x emissions as described in section 4.1.1. (see Photographs 5 and 6). Typical quarl temperature for type II flames was 850 C.

Type III Flames

In general, type III flames have been described as those that undergo a highly confined transition within the burner quarl, resulting in a further expansion downstream of the quarl exit and a second recirculation zone. A restriction on the burner geometry has been that the bluff body blockage ratio should be circa 0.3 and initial swirl level >1.0. In these experiments, a type III flame was formed with a blockage ratio of 0.6, a quarl expansion ratio of 2.0 (i.e. not confined), and secondary air velocities between 68 and 95 m/s.

4.2.4 Effect of Coal Injection Position - Gun B, Oblique Coal Injector

The effect of coal injector position on flue NO_x emissions is shown in Figure 4.6. As with the annular coal injection mode, injector insertion results in a significant drop in NO_x emissions. Unlike that annular coal injector, NO_x emissions are relatively low with the injector at position 0, circa 300 ppm (0% O_2). Firing into the burner throat or using a high swirl level at gun position 0 tend to increase NO_x. The relationship between gun position and T_x is shown in Figure 4.7. Burnout levels between 98 and 99% are realized in most cases.

4.2.5 Effect of Burner Load - Gun A, Annular Coal Injector

Figure 4.9 shows the effect of burner load (2.5 MW = 100%) on NO_x emissions and T_x under two turndown conditions:

- constant V_p, constant V_s. S_o varies with load;
- constant V_p, constant S_o. V_s varies with load.

In both cases, NO_x and T_x decrease with load. This behaviour is due to the initial mixing intensity.

4.3 Detailed In-Flame Measurements

Detailed in-flame measurements were performed on two flames. Input conditions are shown below:

Flame	S_o	V_s (m/s)	V_p (m/s)	Gun Position (mm)	NO_x ppm ($0\%O_2$)	T_x (%)
2	1.0	38	17	0	613	98.4
5	1.0	38	17	+50	356	97.7

These flames were selected for detailed investigation, as they differ significantly in flue NO_x emissions. In terms of burner inputs, the only difference between the two flames is the coal injector position.

Figure 4.14 contains a schematic of the flow patterns observed for the two flames. It can be seen, that a major difference exists as to the location of the initial volatile combustion. For flame 2, the coal stream spread around the IRZ whilst for flame 5 the coal jet penetrated the IRZ. This data indicates that volatile combustion is occurring in a more fuel lean environment for flame 5 than flame 2. Thus lower NO_x is observed for flame 5.

5.0 REPORT CONCLUSIONS

1. For flame 5, initial devolatilization (including volatile N) occurs within the IRZ under reducing conditions.

2. For flame 2, initial devolatilization (including volatile N) occurs on the IRZ boundary, under less reducing conditions.

3. HCN/NH_3 form very rapidly in both flames, but in the case on flame 2, are oxidised rapidly to NO_x, whereas for flame 5 these species react to N_2 preferentially.

4. It seems that it is important for NO_x reduction, to devolatilise in a region where the O_2 concentration is low and the CO concentration is high. These conditions will permit devolatilised nitrogen species to prevail as HCN and NH_3 in a reducing environment, and encourage their decomposition to N_2 rather than oxidation to NO_x.

6.0 COMMENTARY

Two burner concepts have been evaluated in these trials, namely the AASB and the ASPB. These two concepts create a fuel rich zone in two different ways.

The AASB relies on optimization of the near burner field aerodynamics, whereas the ASPB utilizes a pre-combustion chamber, i.e. external to the burner proper, while operating at sub-stoichiometric conditions.

The optimization of both types of burners is coal dependent. Better NO_x reductions were obtained by both burners firing the more volatile Scotts Branch coal than the Heinrich Robert.

As discussed in the commentary for Report #1, the AASB burner is more amenable to retrofit situations.

With respect to the ASPB and its possible development for utility boilers, it is worth noting that the Babcock & Wilcox cyclone furnace, which is specifically designed to burn coals with low ash fusion temperatures, utilizes the concept of "external" combustors (i.e. combustion takes place external to the furnace. Thus, a modified cyclone furnace could be adapted for at least an order of magnitude scaled up ASPB trial.

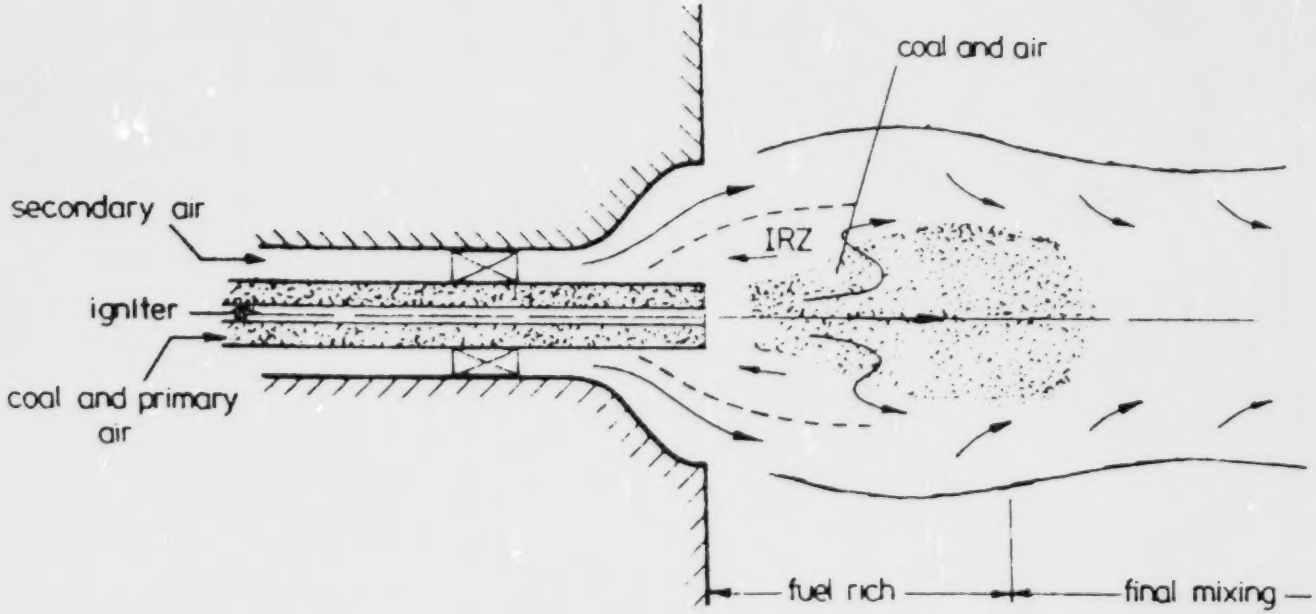


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Fig.3.2 Aerodynamically air staged burner - AP 16

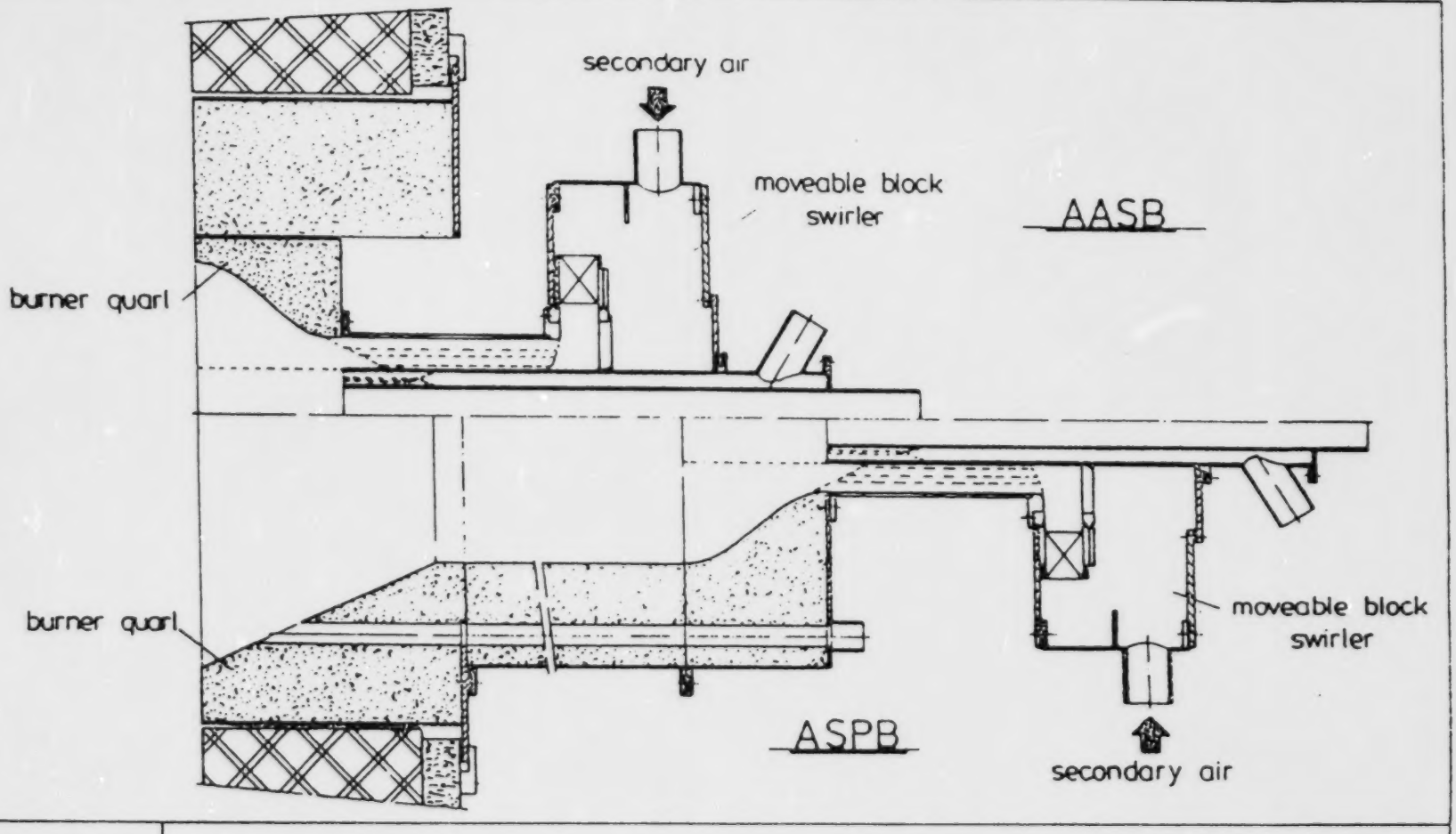

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Fig. 3.3 : Scaled construction drawings of AASB and ASPB

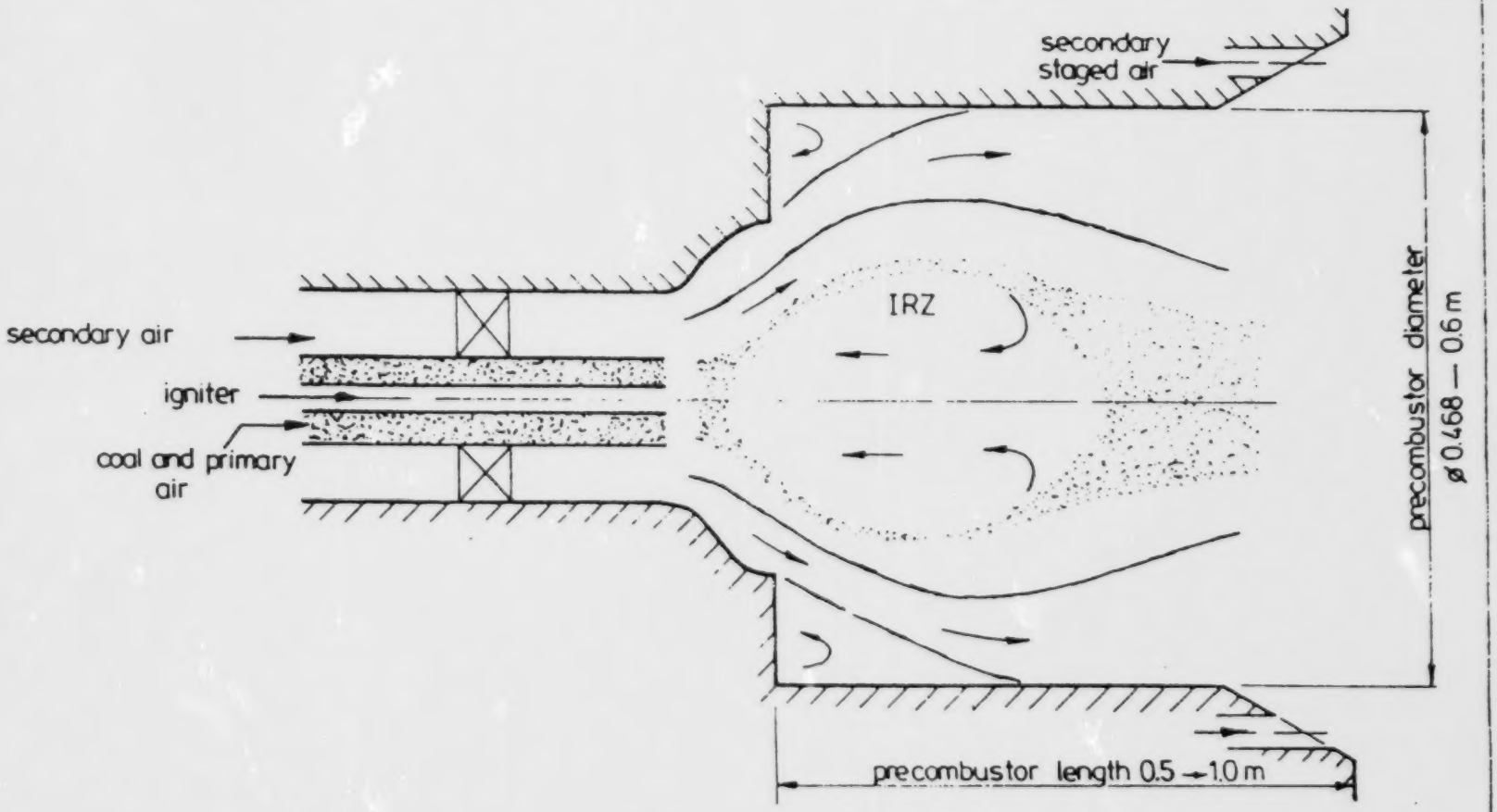

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Fig. 3.6: Air staged precombustor burner - AP 16

	So	Vs	Vp	ṁp
◔	1.0	38	17	500
⊡	2.6	38	17	500
▼	1.0	43	17	200
▲	0.4	43	17	200
⊛	1.0	38	40	500
⊠	0.8	38	40	500

	So	Vs	Vp	ṁp
+	1.0	43	24	200
×	2.6	43	24	200
○	1.0	38	40	500
□	1.0	43	31	200
△	1.0	38	77	500
●	0.8	68	24	200
■	1.3	95	40	500

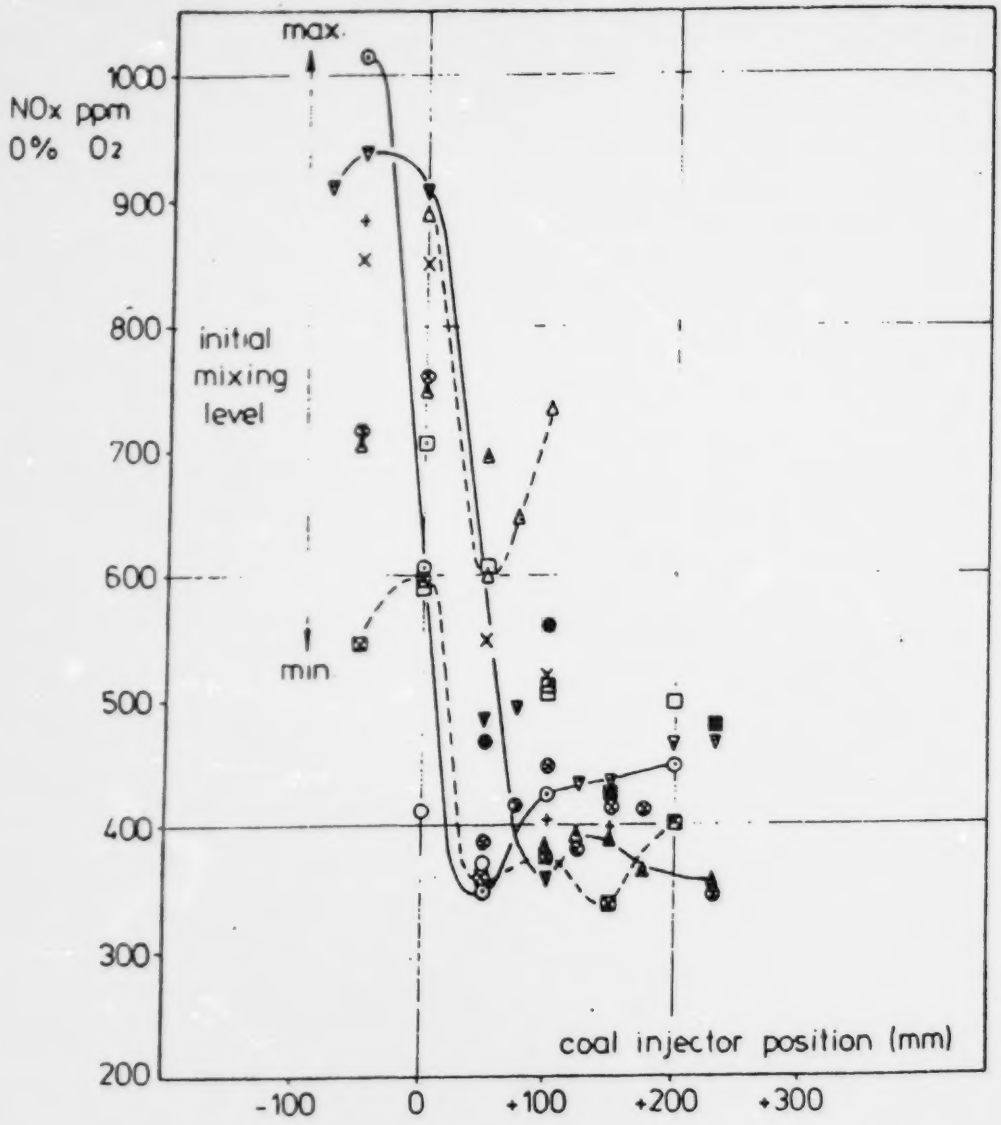

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Fig 4.1 Effect of coal injector position on NOx emission AASB/GA/SB

	So	Vs	Vp	mp
⊙	1.0	38	17	500
△	0.4	43	17	200
⊗	1.0	38	40	500
⊠	0.8	38	40	500
+	1.0	43	24	200
×	2.6	43	24	200

	So	Vs	Vp	mp
○	1.0	38	40	500
□	1.0	43	31	200
△	1.0	38	77	500
●	0.75	68	24	200
■	1.3	98	40	500

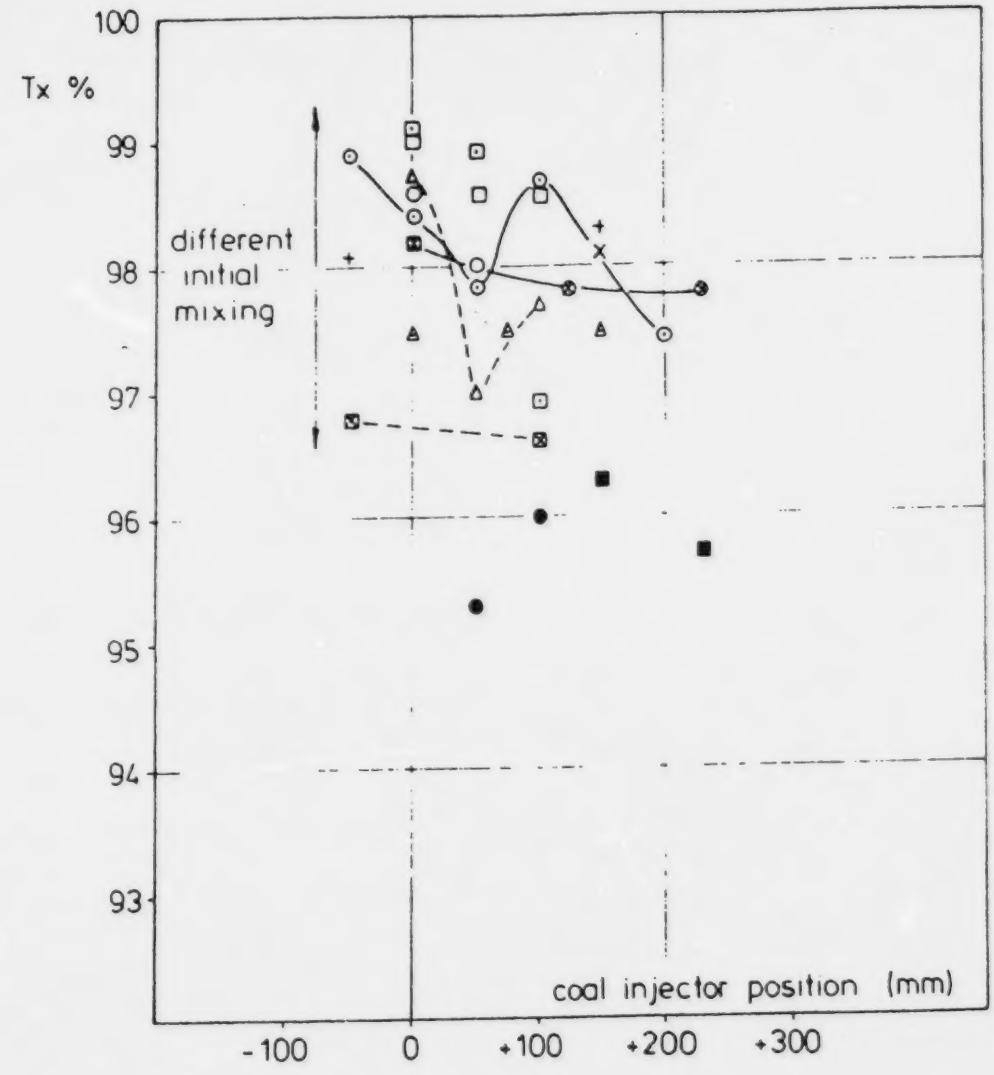

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Fig 4.2: Effect of coal injector on burnout Tx - AASB/GA/SB

	Gp	Vs	Vp	ṁp
⊙	0	38	17	500
⊡	50	38	17	500
⊗	0	43	17	200
+	-50	43	17	200
□	100	43	31	200
△	150	43	24	200
●	-50	43	24	200

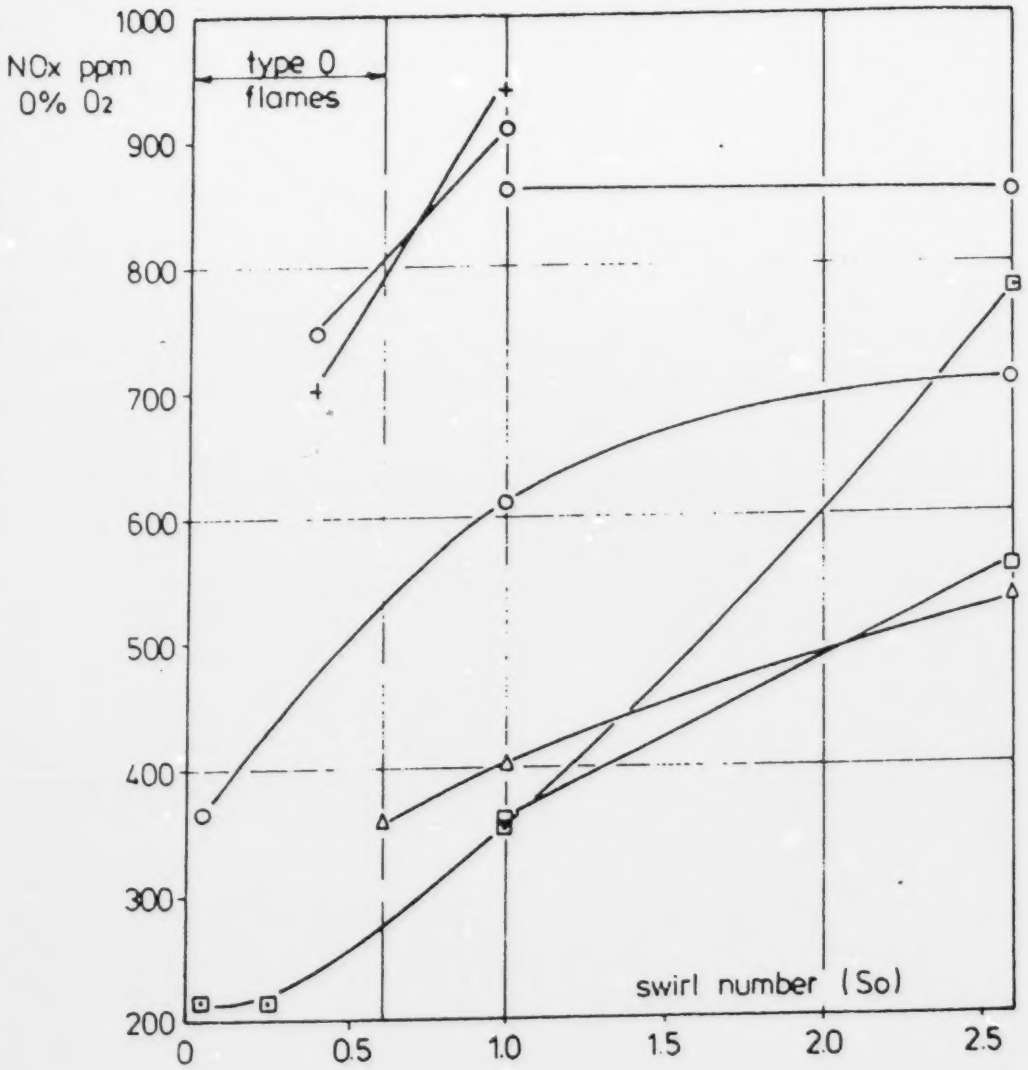

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Fig. 4.4: Effect of swirl number on NOx emission - AASB/GA/SB

	So	Vs	Vp	ṁp
○	1.0	43	31	200
□	2.6	43	31	200
▽	0.6	43	31	200

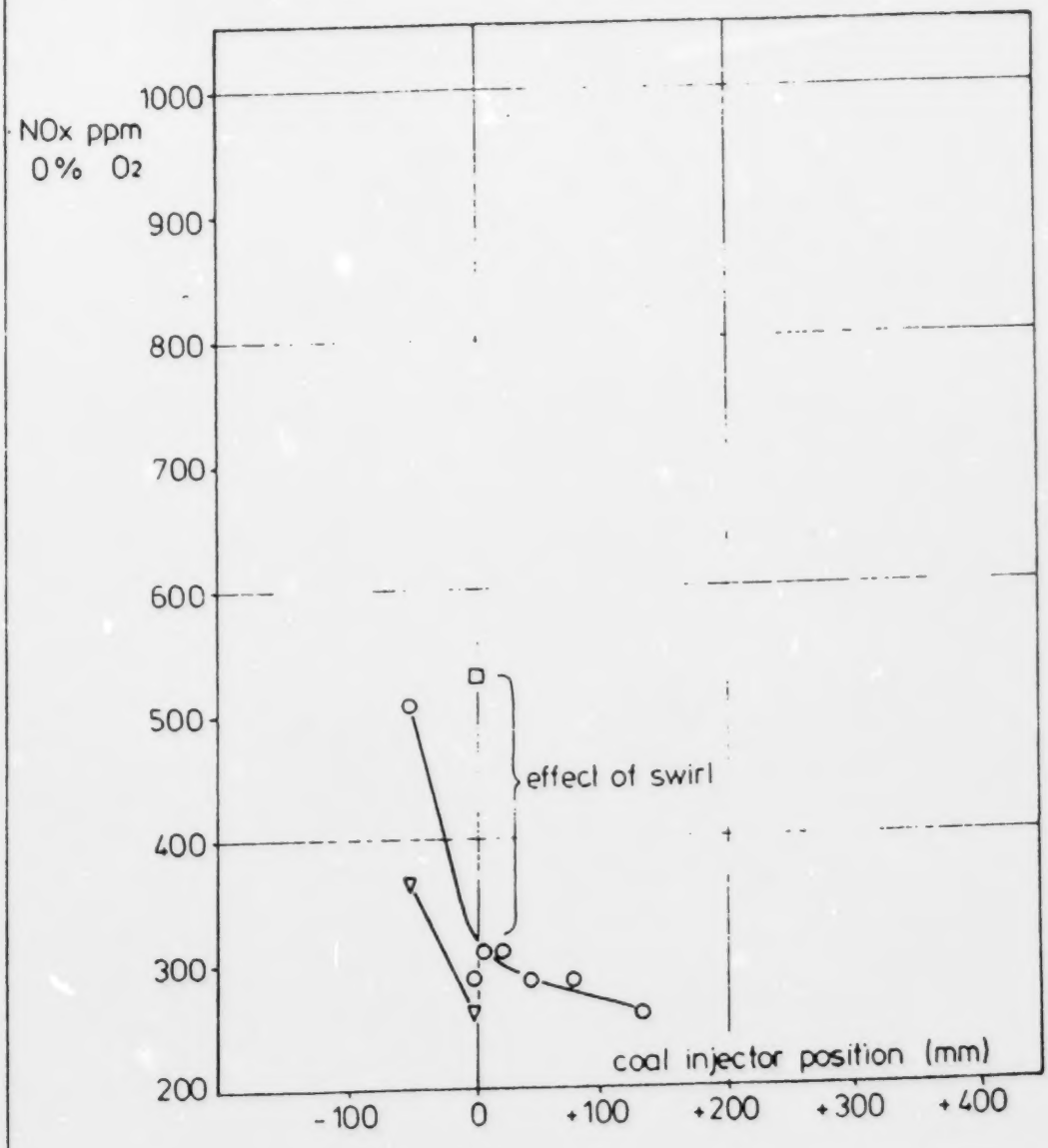

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Fig. 4.6 Effect of coal injector position on NOx emissions - AASB/GB/SB

	So	Vs	Vp	mp
○	1.0	43	31	300
▽	0.6	43	31	200

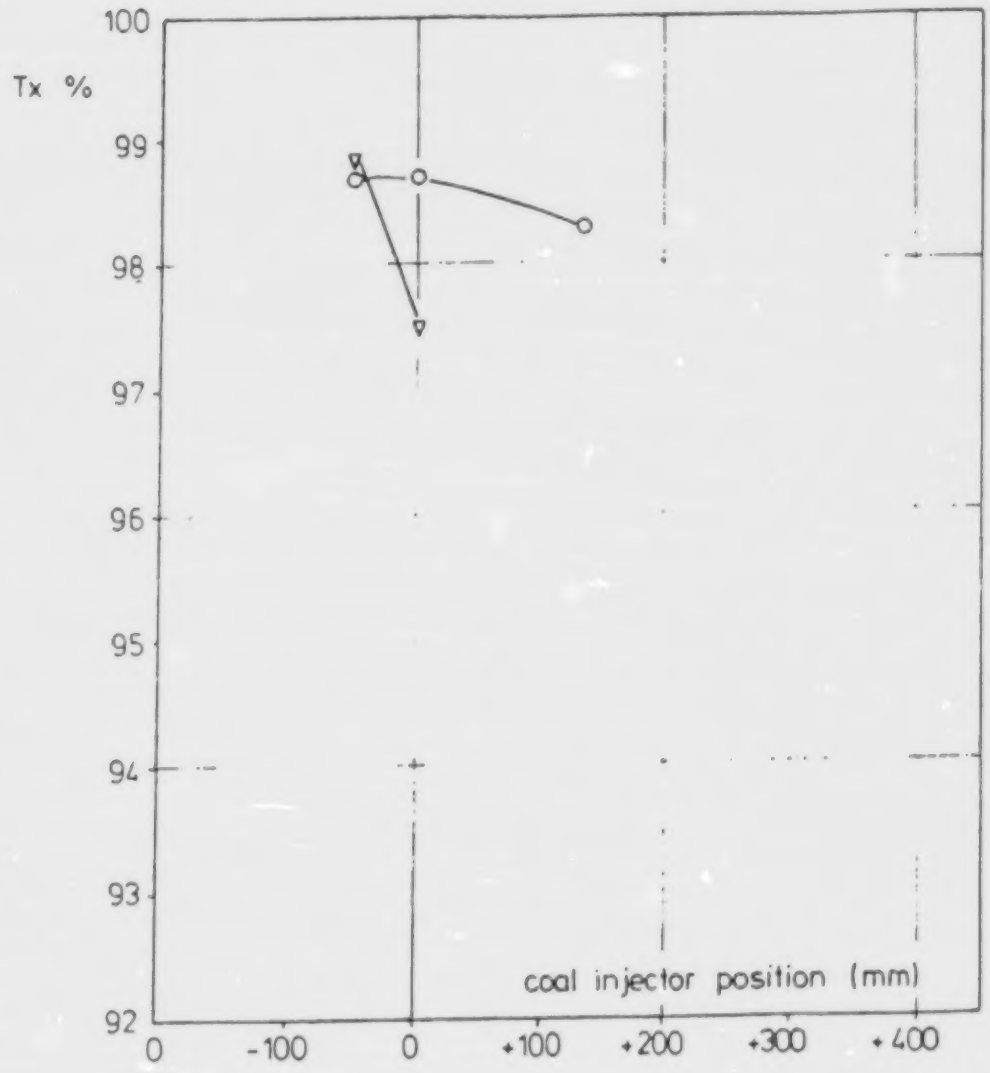

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Fig. 4.7: Effect of coal injector position on burnout (Tx) - AASB/GB/SB

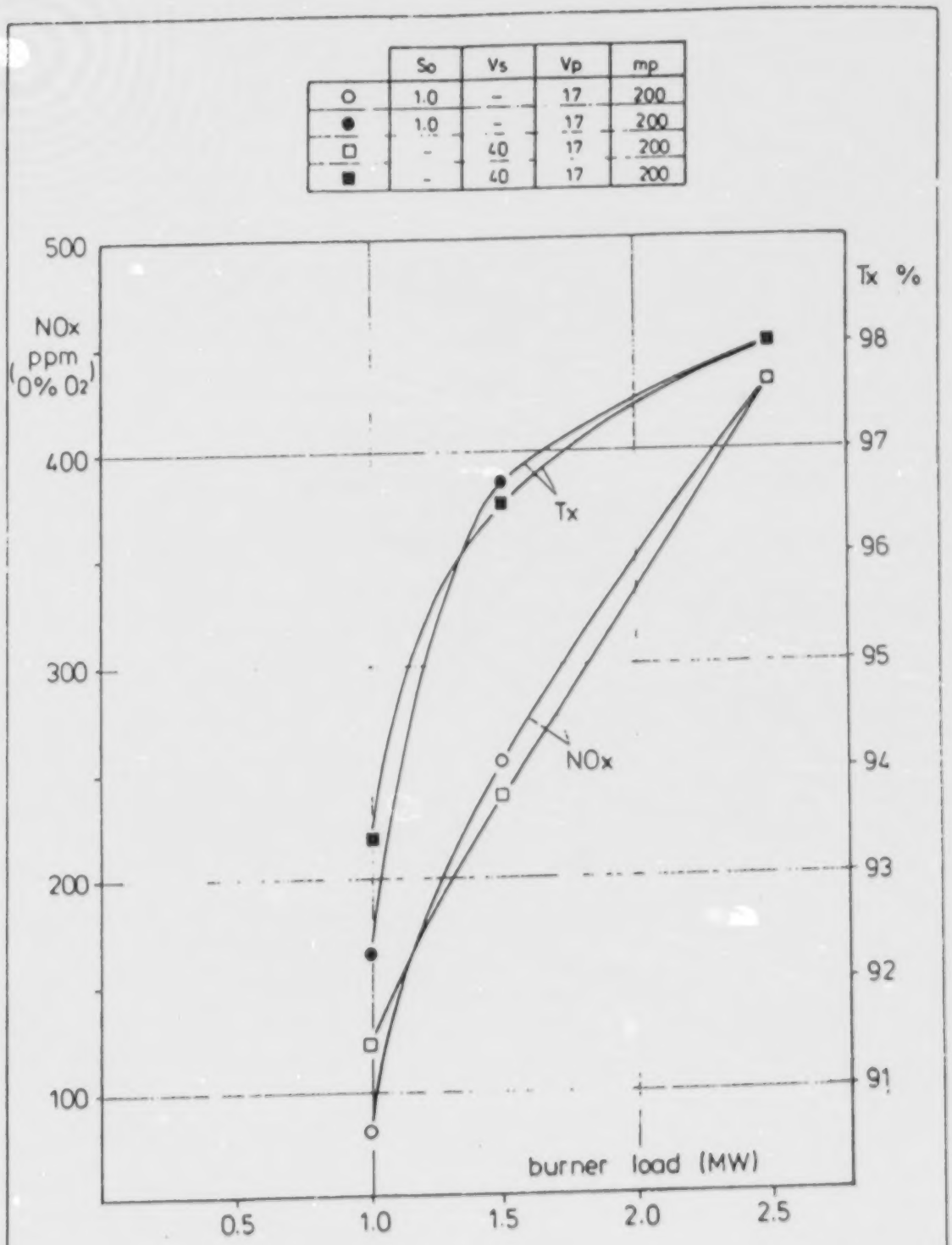

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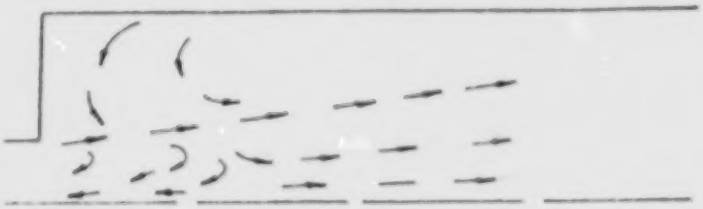
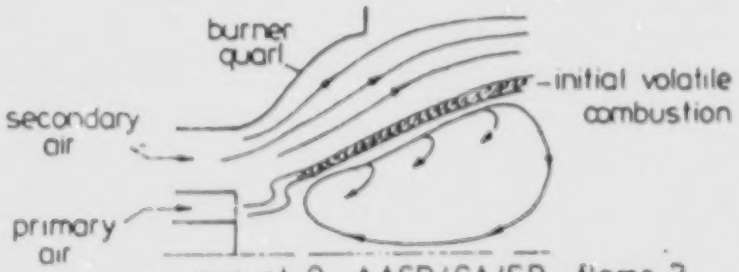
Fig 4.9: Effect of burner load on NOx and Tx - AASB / GA / SB

flow pattern as measured by acetylene probe



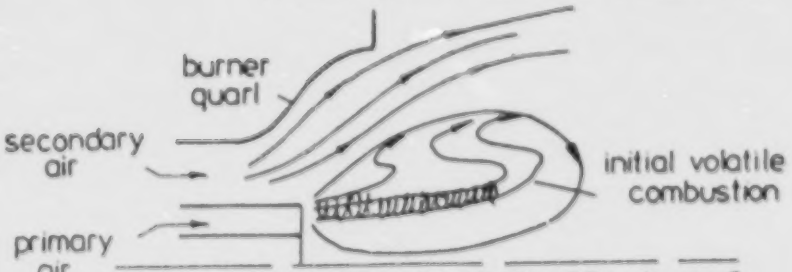
flow pattern within burner quarl



gun at 0 - AASB/GA/SB - flame 2

flow pattern as measured by acetylene probe

flow pattern within burner quarl



gun at +50 - AASB/GA/SB - flame 5

IFRF

Fig. 4.14 : Flow patterns flame 2 and 5

AASB / GA / SB

3.0 REPORT NO. 3

EVALUATION OF RESIDENCE TIME AND TEMPERATURE DISTRIBUTION IN IFRF FURNACE NUMBER 1
Report on the CC 2-1 Investigation

1.0 OVERVIEW

Earlier research using IFRF Furnace No.1 had demonstrated a rather high residual unburnt carbon in ash, expressed as total combustible burnout (T_x). For example, Report #2 recorded burnouts mostly in the range of 95 to 98 percent. This study appears to have been initiated to determine whether the incomplete burnout was inherent in the AASB burner, or resulted from some operating phenomenon within the furnace itself.

Basic furnace parameters such as the nominal residence time (about 6 s) and exit gas temperature (1020°C) suggest that more complete carbon burnout should be achieved. Furthermore, the volumetric heat release rate of about 0.1 MW_t per m is similar to that for many industrial-scale boilers, which characteristically obtain a much higher burnout.

Speculation about the furnace temperature profile prompted further investigation to verify that it was reasonably similar to that encountered in a full-scale furnace. Both residence time and temperature could have significant influence on the accuracy of previous test results and the validity of conclusions regarding carbon burnout and NO_x formation.

2.0 OBJECTIVES

The purposes of this study were to:

(a) Determine the mean residence time and flow characterization of the IFRF Furnace No.1

(b) Evaluate the effects of a change in the furnace temperature distribution by modifying the heat extraction coil locations

3.0 TEST PROCEDURE

3.1 Furnace Residence Time

Tests were performed using the AASB, firing natural gas at a heat input of 2.2 MW_t. A helium tracer stream was introduced at a steady rate at the burner. A measurement probe was used at the furnace outlet to detect the presence of helium in the flue gas, by means of a gas chromatograph containing a thermal conductivity detector.

The 3.0 mm O.D. capillary flue gas probe was too fine to withstand the particulate loading inherent with pulverized coal firing. Hence, it was necessary to conduct the furnace residence time measurements on natural gas. The heat release was calculated to produce flue gas volumes identical to those when firing pulverized coal.

On a prescribed electronic signal, the helium gas supply was terminated, and the rate of decay of the sampling signal was plotted with the use of a high-speed voltmeter. The time interval between the termination of helium injection and initial sensor response indicated the shortest residence time, while the rate of decay of the helium sensor signal was analyzed to determine the mean residence time and time distribution.

3.2 Furnace Temperature Distribution

These tests were performed on the AASB using Scotts Branch coal. Initially, the furnace was fitted with nine cooling coils, spaced throughout the furnace length. These were located to simulate the heat absorbtion pattern in a full-size furnace, particularly in the vicinity of the burner. The initial arrangement was identical to that used for previous AASB burner tests.

In order to evaluate the effects of variations in the furnace temperature profile, tests were made with coils removed successively, from the front. Maximum flame temperatures and complete furnace temperature profiles were recorded for three tests. Carbon burnout and NO_x formation were also recorded to quantify the effect of changes in the controlled variable.

4.0 SYNOPSIS OF TEST RESULTS

4.1 Furnace Residence Time

The flow pattern within IFRF Furnace No. 1 is evidently more complex than was originally perceived.

The curves showing the rate of decay of helium concentration in the flue gas were corrected to allow for the sensing system time delay, and were converted mathematically to a residence time distribution (RTD) plot. This depicts the proportion of combustion products reaching the furnace exit at successive time intervals following the step change in helium input.

The results of this analysis revealed an unexpected flow regime in the furnace. Although the mean furnace residence time was shown to be 6 seconds, the first combustion products actually reached the furnace exit in 0.34 seconds. Moreover, about 8 percent of the tracer was seen to emerge from the furnace in approximately 0.8 seconds. This was interpreted as a plug flow zone, which effectively bypassed a larger dispersed zone within the furnace.

Application of these results to the furnace dimensions suggested that about 2.1 m of the volume was effectively stagnant, and this contributed to the long tailing-off of the tracer concentration recording (Figure 4.3).

4.2 Furnace Temperature Distribution

As the front three furnace cooling coils were removed successively from the furnace, the flame temperature showed an increase from 1550°C to 1600°C. The furnace temperature profile showed the predictable increase, as did the furnace exit temperature.

Flame No.	No. of Coils	Flame Temp.	Furn. Exit Temp.	NOx (ppm)
4	9	1550°C	1020°C	610
5	8	1600°C	1040°C	726
6	7	1600°C	1050°C	930

Carbon burnout proved to be almost insensitive to the higher flame and furnace temperatures. However, the NO_x level in the flue gas increased steadily with each successive coil removal. At least part of this increase was believed to be due to thermal NO_x formation, which becomes significant at flame temperatures greater than about 1540°C. However, this did not explain the increase between flames 5 and 6.

Furnace temperature profiles were recorded for all three flames. Interestingly, these seemed to substantiate the presence of a bypass channel of flow which appears to envelope the more stagnant centre core (Figures 5.1, 5.3, 5.5).

5.0 REPORT CONCLUSIONS

1. Although the furnace mean residence time is about 6 seconds, the furnace flow is characterized by a "plug flow" region with a residence time of about 0.34 seconds, followed by a "dispersed flow" region with a residence time of 5.66 seconds.

2. A significant portion of the tracer element (approximately 8%) reached the furnace exit between 0.34 and 1.24 seconds. This may account for the unexpectedly high carbon burnout in previous tests.

3. The calculated furnace "dispersion number" of 0.9 would tend to indicate considerable back-mixing within the furnace, resulting in an extended residence time.

4. Modifications to the heat extraction profile of the furnace can produce near-burner-zone temperatures similar to full-scale flames, but the residence time in these high temperatures is shorter than in full-scale flames.

5. Carbon burnout is not affected by coil removal and resulting variations in furnace temperature profile.

6. NO_x formation is directly related to the furnace temperatures in the vicinity of the burner, although at the flame temperatures recorded, thermal NO_x may account for some of the increase between flame numbers 5 and 6.

7. Full-scale residence time and temperature profiles can be only partially simulated in IFRF Furnace No.1.

6.0 COMMENTARY

The statistical portrayal of the residence times of particles within a furnace is evidently much more complex than suggested by the simplified volumetric calculations typical of many boiler specifications.

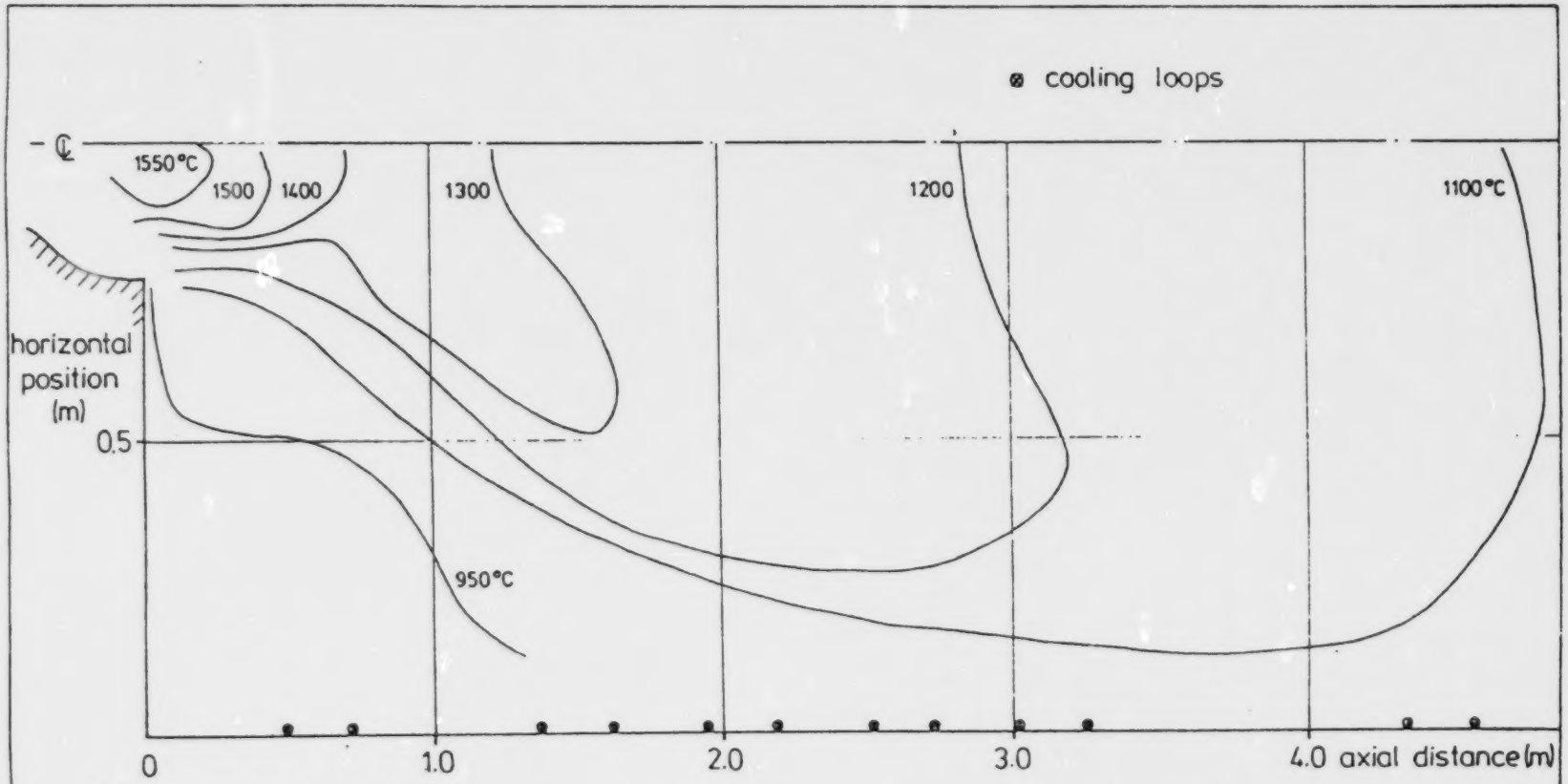
Several references are made to the furnace dispersion number (D/uL=0.9) and this would appear to be an important index for comparison of full-scale furnace operation. Unfortunately, the derivation of this index is omitted, although reference sources are provided (Ref. 15). Further description of the development and interpretation of the dispersion number would be a useful appendix to this report, and would probably be valuable in relation to full-scale furnace performance.

No mention is made of the location(s) of the helium sample probe within the furnace exit duct, or whether traverses were made to determine the most representative locations. In view of the channelling effect previously mentioned, some comment about the effect of probe location would be appropriate.

Considerable mathematical modelling was performed in order to determine reaction rates for the conversion of HCN to either NO or NO_2. This was identified as a possible explanation for the increase in NO_x production of about 200 ppm between flames 5 and 6. Correlation of the calculated rates of reaction with the rapidly-changing furnace temperatures seems to have been somewhat speculative. However, the calculations do appear to substantiate the temperature effects on the HCN conversion as a viable explanation of the observed increase in NO_x level.

Some comment on the relationship between HCN evolution and coal characteristics would be beneficial in projecting this aspect to other fuels.

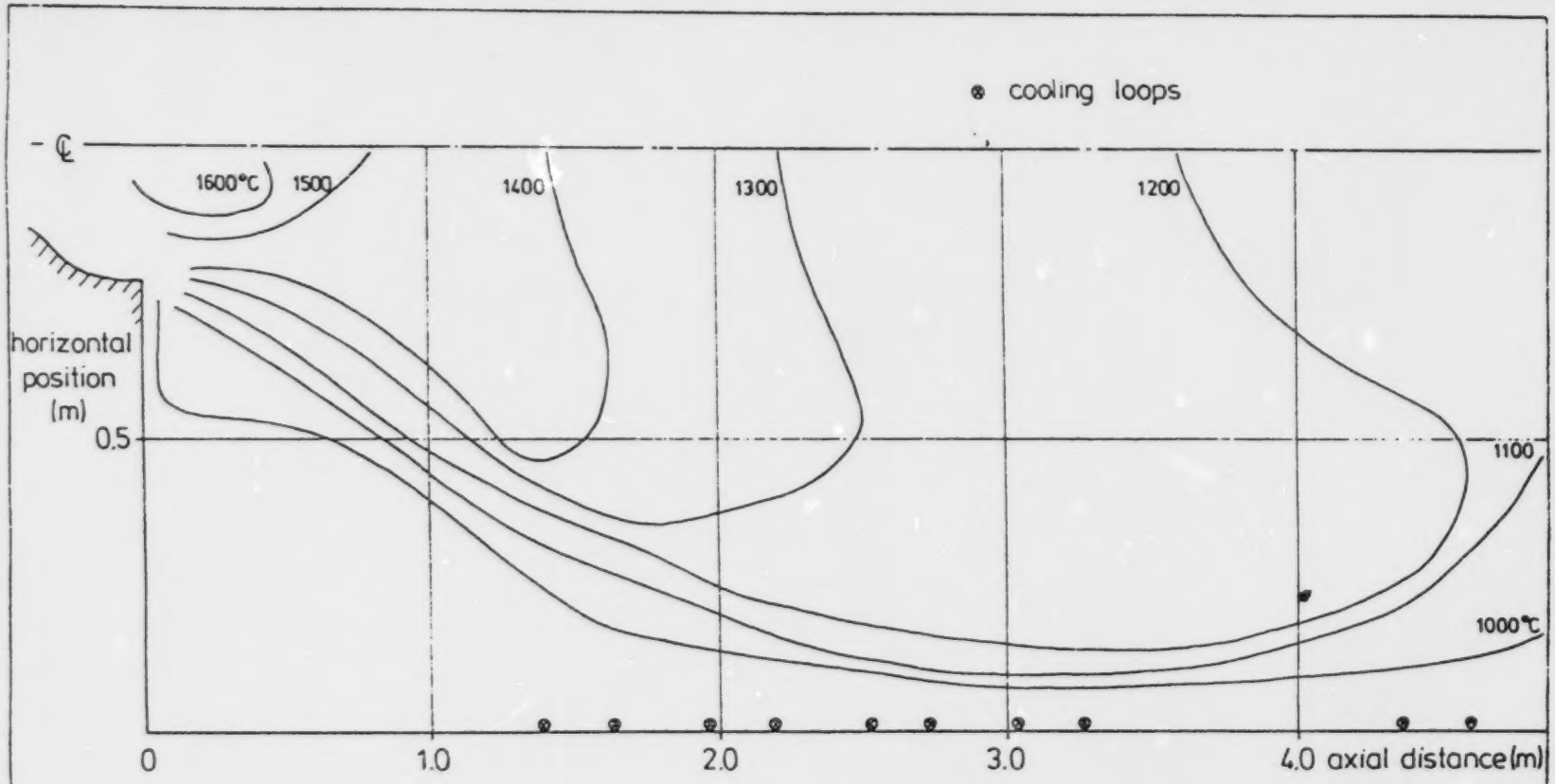
Several useful design parameters are presented in the report, for example; "...the degree of cooling in the first 2 meters of the furnace is critical in determining NO_x emissions." as well as the various residence time and flow regime criteria.



IFRF

Fig. 5.1: Temperature distribution - 9 cooling loops

Flame #4
(Lille Nov)



IFRF

Fig. 5.3 : Temperature distribution - 8 cooling loops

3.0 REPORT NO. 4

EFFECT OF COAL PARTICLE SIZE AND GUN DESIGN ON NO_x REDUCTION USING AN AERODYNAMICALLY AIR STAGED BURNER
Report on the CC 2-2 Trials

1.0 OVERVIEW

In Report #1, three different internally air staged burners equipped with annular coal guns were evaluated. Two of the burners, an aerodynamically air staged burner (AASB) and an air staged precombustor burner (ASPB), resulted in very low NO_x emissions when compared to baseline levels. The NO_x emissions were as low as 320 ppm (0% oxygen) with a burnout of 98% using a high volatile bituminous coal.

Both of these burners were studied in more detail in Report #2. High and low volatile bituminous coals were fired under different conditions. The effects of swirl level, gun position, primary air momentum and coal type on NO_x emissions were systematically investigated. The gun was inserted to promote the initial devolatilization within the IRZ resulting in lower NO_x emissions and lower sensitivity to initial mixing levels.

In order to increase IRZ penetration using the AASB, a second gun, called the oblique coal gun, was used in which coal was injected obliquely through four equidistant holes instead of around the entire annulus. The optimum NO_x emission level using this oblique coal injector was 240 ppm (0% oxygen) at 98% burnout compared to 320 ppm (0% oxygen) at 98% burnout for the annular coal injector.

The effect of particle size distribution on NO_x emissions from a pulverized coal flame has not been studied extensively. This may be due, in part, to the limited commercial range of fuel particle sizes for utility boilers, since historically, coal particle size distribution was a matter of economics.

The reported difference in devolatilization rate may have a significant effect on the NO_x reduction potential using the aerodynamically air staged burner. In these experiments, the length of time the particle is in the IRZ is maximized by optimizing the particle penetration depth without escaping out the downstream end of the IRZ. This optimization may be obtained by altering the primary jet momentum, gun insertion depth or the secondary air swirl level. These three variables were optimized for each particle size studied.

2.0 OBJECTIVES

(a) To determine the effect of particle size distribution on NO_x emissions and carbon burnout from the aerodynamically air staged burner.

(b) To measure the advantage of the oblique coal gun relative to the annular coal gun to reduce NO_x emissions.

3.0 TEST PROCEDURE

3.1 Furnace

The experimental programme was executed on the IFRF No. 1 furnace as shown in Figure 3.1. The furnace has internal dimensions of 2.0 x 2.0 x 6.25 m and is fitted with seven cooling loops concentrated toward the exit of the furnace. The cooling loop configuration was the final one used in the CC 2-1 experiments (Report #3). The cooling loops removed approximately 45% of the total thermal input resulting in a flue gas temperature of 1050°C.

Burner thermal input was set at 2.5 MW corresponding to a volumetric firing density of 0.1 MW/m . The coal accounted for approximately 92% of the total thermal input and the combustion air preheat, the remainder.

3.2 Burner

The aerodynamically air staged burner, shown schematically in Figure 3.2, was used for all of the tests. This burner consisted of moveable coal and gas guns, a moveable block swirl generator and a "tulip-shaped" quarl.

Three different coal guns were employed to test the effect of primary air momentum, velocity and injection configuration on NO_x emissions. The three guns are shown in Figure 3.3. Gun A was an annular coal injector which produced a bluff body ratio of approximately 0.6. With this gun, coal was injected with transport air of mass flow rate 500 kg/h. The resulting injection velocity was 19 m/s. Gun B was an oblique coal injector in which the coal jet was separated into four independent streams of circular cross-section. This gun was also designed with a bluff body ratio of 0.6 and a transport air mass flow rate of 500 kg/h. Gun C was an oblique coal injector designed with a bluff body ratio of 0.6 and a primary air mass flow rate of 300 kg/h. The standard jet velocities for the oblique guns were 19-20 m/s but could be increased to 33-39 m/s in Gun B by using inserts and in Gun C by increasing the primary air mass flow rate to 500 kg/h.

The coal guns could be inserted up to 150 mm beyond the entrance into the quarl (see Figure 3.2). Gun insertion was varied by adjusting the coal gun position relative to the burner throat. Swirl was generated by using an IFRF moveable block swirler. The swirl generator calibration is shown in Figure 3.4.

3.3 Instrumentation

The following instrumentation was used to measure the furnace outlet gas composition and to collect solid samples.

Solid	-	IFRF Alcan-probe (bronze filter).
Gas	-	IFRF Alcan-probe (glass wool filter).
NO_x	-	Chemiluminescent analyser.
O_2	-	Paramagnetic analyser.
CO_2	-	Infra-red analyser.
CO	-	Infra-red analyser.
Temperature	-	Section Pyrometer with Pt-Pt/Rh (10%) thermocouple.

3.4 Coal Selection

All parametric studies were completed using Scotts Branch high volatile bituminous coal. The Scotts Branch coal was dried, crushed and milled to obtain 56, 75 or 93% less than 200 mesh (75 um). The particle fraction smaller than 75 um was determined by dry sieve analysis on samples taken after the pulverizer.

The particle size fraction measured by dry sieve analysis was compared with measurements using wet sieve analysis. As shown in Table 3.2, the fraction of material less than 75 um measured by dry sieve analysis was within 5% of the measurements using wet sieve analysis. The wet sieve particle size distribution could be modelled using a Rosin-Rammler distribution, which is the normal distribution of particle size for pulveried coal.

3.5 Analysis

3.5.1 Heat Extraction

Heat extraction from the furnace was monitored by calorimetry in the seven cooling loops installed in the furnace. The first 2 m of the furnace were uncooled compared to 1.1 m in Report #2.

3.5.2 Carbon Burnout

Carbon burnout was calculated from an ash balance of the input coal and combustion residue according to the equation:-

$$T_x = \frac{1 - \frac{\text{ash (coal)}}{\text{ash (residue)}}}{1 - \text{ash (coal)}}$$

3.5.3. Experimental Design

The Box-Behnkin experimental design was used to study simultaneously the effect of coal particle size, swirl number and gun position on NO_x emissions using Guns A, B

and C. This technique employs a subset of the points in the corresponding full three-level factorial experimental design. By using the Box-Behnkin design, a response surface type model of the effect of the selected variables on NO_x emissions may be constructed with a minimum number of experimental tests. The experimental conditions required to obtain the response surface model are shown in Table 3.3.

4.0 SYNOPSIS OF TEST RESULTS

4.1 General

The results of all flames studied, including their process conditions, are listed in Table 4.1a and b. Complete Box-Behnkin experimental test designs were conducted for the axisymmetric annular coal gun (Gun A) and the oblique coal gun (Gun C) with primary air mass flow rate of 300 or 500 kg/h. In addition, the effects of primary air velocity and primary air mass flow rate were studied independently in the oblique coal Guns B and C.

In general, the carbon burnout and NO_x emissions were higher than reported in previous experimental tests using the AASB as illustrated in Figure 4.1. The NO_x emissions increased by an average of 250 ppm and the carbon burnout increased by approximately one percent over Report #2 tests. The increase in NO_x emissions and carbon burnout has been attributed to a different arrangement of cooling loops in Furnace No. 1 in the two trials.

4.2 Results of the Annular Gun

The burner was operated with the annular coal gun (Gun A) in Flames 1-6, 31-34 and 51-54. The baseline conditions of normal grind coal, gun position of 0 mm and a swirl level of 0.7 produced a NO_x emission of 1150 ppm in Flame 5. However, up to 50% reduction in NO_x emissions was possible for optimized flames.

4.2.1 Effect of Particle Size Distribution

The effect of particle size distribution (PSD) on NO_x emissions was small. Over the entire range of gun positions and swirl levels studied, finer PSD increased NO_x emissions by an average of 15 ppm. However, there was some influence of PSD on NO_x emissions at particular gun positions. When the gun was located at 0 mm, NO_x emissions increased by 57 ppm as the fraction of coal smaller than 75 um increased from 0.56 to 0.93. At a gun position of 150 mm, the reverse effect was estimated and the finer grind coal was predicted to have a 200 ppm lower NO_x emission level than the coarser grind coal. However, a type II flame with a stable IRZ could not be produced with the gun at 150 mm. The maximum possible insertion depth using fine grind coal was cited at 135 mm with a NO_x emission reduction of 122 ppm. This compares to a coarser particle

size which allowed a gun postion of 150 mm but NO_x levels in excess of 600 ppm.

The influence of coal PSD on carbon burnout is shown in Figure 4.4. At all NO_x emission levels, the coarse grind coal has a relatively high carbon in ash content of 6-14%. The normal and fine grind coals had carbon in ash of 2-5%. For the coarser grind coal, carbon in ash was adversely affected by NO_x reduction techniques. Carbon in ash increased from 6% at a NO_x emission level of 1150 ppm to 14% at a NO_x emission level of 700 ppm. The carbon in ash levels were relatively insensitive to NO_x emission reduction techniques for the normal and fine grind coal. Carbon in ash was 2-3% for NO_x emissions of 700-1300 ppm. At 550 ppm NO_x emissions level, the carbon in ash rose to 5% for the normal grind but remained at 2-3% for the fine grind.

4.2.2 Effect of Gun Position

Gun position was the dominant parameter affecting NO_x emissions. With a swirl level of 1.2 and normal grind coal, gun insertion from 75 to 150 mm resulted in a 53% reduction in NO_x emissions until the distance exceeded 75 mm. This observation is apparent from the negative curvature in the response surfaces of NO_x emissions in Figure 4.2.

The effect of gun position on flame structure may be compared directly in Photographs 1 and 2. Photograph 1 was taken from Flame 1, produced using Gun A at a gun position of 0 mm and swirl level of 1.2. The flame length was approximately 0.5 m and the NO_x emission was 1150 ppm. Photograph 2 was taken in Flame 4, produced at a gun position of 150 mm and a swirl level of 1.2. The flame length was 1.3 m and the NO_x emission decreased by 53% to 550 ppm. The additional gun insertion resulted in a higher concentration of particles projected into the IRZ.

4.2.3 Effect of Swirl Level

The effect of swirl on NO_x emissions is shown in Figure 4.2. Increasing swirl from 0.7 to 1.2 at a gun position of 75 mm with normal grind coal, resulted in a predicted average increase in NO_x emission of 130 ppm from Equation 3.4. At a gun position of 0 mm, the NO_x emission was independent of swirl number. Flames 5, 53 and 3, produced at swirl level of 0.7, 1.2 and 1.7, had NO_x emissions of 1150, 1170 and 1060 ppm, respectively. Almost no particles were able to penetrate the IRZ at any swirl level. At increased gun insertion, NO_x emissions increased at higher swirl level. At a gun position of 150 mm, NO_x emission increased from 550 ppm for Flame 4 at a swirl level of 1.2 to 780 ppm for Flame 2 at a swirl level of 1.7.

Therefore, swirl has a negative impact on NO_x emissions when particle penetration into the IRZ has been achieved.

4.2.4 Optimum NO_x Emissions

A 52% reduction on NO_x emissions from a baseline value of 1150 ppm to 550 ppm was possible using Gun A. Carbon in ash was not adversely affected by the NO_x reduction with values lower than 5% possible at the lowest NO_x emission levels for normal and fine grind coals. The optimum NO_x emission was 550 ppm with 5% carbon in ash. This was obtained from Flame 4 with normal grind coal, swirl of 1.2 and 150 mm gun position.

4.3 Results of the Oblique Gun Operated at a Low Momentum Flux

The burner was installed with the oblique coal gun (Gun C) and operated at a low primary air momentum flux in flames 7-12, 35-38 and 55-58. The low momentum flux was attained by injecting the coal in primary air at a mass flow rate of 300 kg/h and a velocity of 19 m/s. At this condition, the primary air momentum flux was 1.67 N. The baseline conditions of normal grind coal, a swirl level of 0.7 and a gun position of 0 mm produced a NO_x emission of 1120 ppm in Flame 11. A 45% reduction on NO_x emissions was possible for optimized flames.

4.3.1 Effect of Particle Size Distribution

Particle size distribution did not have a significant effect on NO_x emissions when using Gun C. The maximum difference in NO_x emissions due to PSD at any given process conditions was 87 ppm. Normal and fine grind coal had identical NO_x emissions at all swirl levels and gun positions investigated. This effect may be visualised by the flat response surfaces for NO_x emissions as a function of PSD illustrated in Figure 4.5.

4.3.2 Effect of Gun Position

As was the case with Gun A, gun position was the dominant parameter affecting NO_x emissions. Predicted NO_x emissions for Gun C, (Equation 3.4), decreased from 1100 to 630 ppm as the coal gun position was changed from 0 to 150 mm. NO_x emissions decreased as Gun C was inserted up to 75 mm. Further gun insertion did not significantly lower NO_x emissions. However, NO_x emissions, using Gun A, did not decrease until the gun was inserted 75 mm. This difference may be due to the oblique gun concentrating the coal into four jets thereby increasing IRZ penetration.

4.3.3 Effect of Swirl Level

Swirl level had a small effect on NO_x emissions for Gun C operated at a low momentum flux. The NO_x emissions decreased by up to 70 ppm when the swirl level decreased from 1.7 to 1.2. Flames 36 and 56, produced at a swirl

level of 1.7, had NO_x emissions of 830 and 740 ppm respectively, compared to Flames 7 and 12, produced at a swirl level of 1.2, which had NO_x emissions of 760. Further decreases in swirl level did not affect NO_x emissions. The NO_x emissions from Flames 35 and 55, produced at a swirl of 0.7, were 750 and 770 ppm, respectively. As concluded in the previous subsection, mixing of the coal jet and the recirculated oxygen rich gases was not significant for the oblique gun operated at a low momentum flux.

4.3.4 Optimized NO_x Reduction

It was shown that a 45% reduction in NO_x emissions from 1120 ppm to 610 ppm was possible using Gun C operated at a low momentum flux. Flame 10 had the lowest NO_x emission of 610 ppm. This flame was obtained with a normal grind coal at a swirl level of 0.7 and a gun penetration of 150 mm. As was the case with Gun A, carbon in ash was not adversely affected by the NO_x reduction as shown in Figure 4.6. For Flame 10, the carbon in ash was 3.5%.

4.4 Results of the Oblique Gun Operated at a High Momentum Flux

The burner installed with Gun C was also operated at a high momentum flux of 5.4 N by increasing the primary air mass flow rate to 500 kg/h and the velocity to 33 m/s. Flames 12-18, 39-42 and 59-62 were produced using this arrangement. The baseline conditions of normal grind coal, a swirl level of 0.9 and a gun position of 0 mm produced a NO_x emission of 790 ppm on Flame 17. A 46% reduction was possible under optimized conditions.

4.4.1 Effect of Particle Size Distribution

The particle size distribution had a significant effect on the NO_x emission reductions from Gun C operated at a high primary momentum flux. In general, the NO_x emission decreased with smaller PSD. Flame 62, produced using fine grind coal at swirl level of 1.2 and gun position of 150 mm, had a NO_x emission of 500 ppm compared to Flame 42, produced using coarse grind coal which had NO_x emission of 620 ppm. This effect was due to larger diameter particles escaping the downstream end of the IRZ and mixing with oxygen rich gases. This effect can be seen clearly in Photographs 3 and 4 which were take in Flames 62 and 42, respectively.

4.4.2 Effect of Gun Position

Although gun position was the dominant factor affecting NO_x emission reduction using Gun C, the influence was much less than was observed when operated at a low momentum flux. The NO_x emissions, predicted using Equation 3.4, would decrease by 230 ppm for a swirl level of 1.2 and normal grind coal when the gun position changed from 0 to 150 mm.

Most of the influence was observed in the first 75 mm. Flame 61, produced at a gun position of 0 mm, had a NO_x emission of 780 ppm compared to Flame 18, produced at a gun position of 75 mm, which had a NO_x emission of 560 ppm. Additional gun insertion may have resulted in partial escape of coal particles out the downstream end of the IRZ. Flame 16, produced at a gun position of 150 mm, had the same NO_x emission as Flame 18.

4.4.3 Effect of Swirl Level

Swirl level had a significant effect on NO_x emissions. The NO_x emission decreased from 610 ppm for Flame 60 and 420 ppm for Flame 59 as swirl was decreased from 1.7 to 0.7. This effect may be attributed to increased mixing of the coal jet with recirculated oxygen rich gas products at high swirl levels.

4.4.4 Optimum NO_x Emissions

For Gun C, operated at a high momentum flux, the optimum NO_x emission obtained in Flame 59 was 425 ppm. As shown in Photograph 6, Flame 59 was a jet type flame produced from fine grind coal at a swirl level of 0.7 and 75 mm gun position. The independent coal jets are visible in the photograph. However, performance of the flame could be considered acceptable since the flame remained attached to the gun. The carbon in ash was 6.5% and the flame length was 1.0 m.

5.0 REPORT CONCLUSIONS

1. From the experimental results, the following conclusions were reported for the NO_x emissions reduction potential of the AASB using an annular coal gun:

   (a) Baseline NO_x emissions were 1150 ppm and could be reduced to 550 ppm at optimized conditions (S_o = 1.15; gun position = 150 mm; normal grind).

   (b) At this optimized condition, carbon in ash was 5.0%.

2. Using an oblique coal gun, the following conclusions may be made:

   (a) The momentum flux of the primary air must be higher than 3.0 N in order to obtain significant penetration of the IRZ.

   (b) When operated at a high momentum flux, baseline NO_x emissions were 794 ppm and could be reduced to 425 ppm at optimized conditions (S_o = 0.7; gun position = 150 mm; fine grind).

3. NO_x emissions were relatively insensitive to particle size distribution. However, finer coal grind was preferable to stabilise a type II flame at low swirl conditions.

6.0 COMMENTARY

The primary objective of Report #4 was to determine the effect of particle size distribution on NO_x reduction and carbon burnout using the AASB. The secondary objective was to compare the performance of the oblique injection coal gun with the more standard annular injection coal gun.

The annular coal gun (Gun A) consisted of flame numbers 1-6, 31-34 and 51-54, as shown in Table 4.1 (a). These fifteen trials comprise swirl numbers of 0.7 (3), 0.9 (1), 1.2 (7), and 1.7 (4).

Using three other variables, coal particle size (PSD), gun position (Gp) and NO_x, a Box-Behnkin technique has been used for graphical predictions of the variables shown in Figure 4.2. The theory of the Box-Behnkin procedure is dealt with in the Report, together with statistical techniques used for testing the accuracy of the coefficients required for predictions, as shown in equation 3.4.

Interpretation of Figure 4.2 shows PSD has some effect on NO_x emissions for various gun positions and swirl levels. When the gun was at 0 mm, NO_x levels increased as the fraction of fine coal increased. At a gun position of 150 mm, the reverse effect took place and the finer coal decreased the NO_x level by 220 ppm.

Thus it is concluded that PSD for different gun positions is influenced by penetration into and devolatilized in the IRZ. The influence on PSD on carbon burnout is shown in Figure 4.4, and, as expected, carbon burnout improves with decreased coal size.

Gun Position was the more dominant factor in affecting NO_x emissions. With a swirl level of 1.2 and normal coal grind, it can be seen that NO_x decreased from 1170 ppm in flame 1 to 550 ppm in flame 4.

The effect of swirl level on NO_x is also shown in Figure 4.2. Increasing swirl number increases NO_x level. Also, at increased gun insertion NO_x emission levels increased. Therefore, increasing swirl has a negative impact on NO_x emissions after particle penetration into the IRZ has been achieved.

From a NO_x baseline data of 1150 ppm it was possible by using Gun A to reduce to 550 ppm.

The oblique gun (Gun C) was operated in a similar manner with respect to PSD, gun position and varying swirl number. In addition, two further variables were introduced, namely operating the gun at high and low momentum fluxes. That is, high mass flow combined with high primary air velocity and low mass flow combined with low primary air flow.

PSD at low momentum flux did not have a significant effect on NO_x emissions. Normal and fine grind coal had identical NO_x levels for all swirl numbers and gun positions investigated. This can be seen from the Box-Behnkin predictions shown in Figure 4.5.

As for Gun A, the gun position for low momentum flux was the dominant factor in affecting NO_x emissions. Predicted NO_x emissions for Gun C using equation 3.4, (Report p.7), fall from 1100 ppm to 630 ppm when changing the gun position from 0 mm to 150 mm. Also the effect of gun position on NO_x levels was not influenced by swirl number, over the range 0.7, 1.2 and 1.7. Swirl number at low momentum flux also had little impact on NO_x levels.

Operating at low momentum flux, the lowest NO_x level was 610 ppm, which was obtained with a normal grind coal and a swirl level of 0.7, with a corresponding carbon in ash of 3.5%.

When Gun C was operated at high flux levels, i.e. a high mass flow and high primary air velocity, lower momentum flux or when using Gun A. This is attributed to significant penetration of the coal particles into the IRZ, together with physically separating the coal from the recirculated gases by concentrating the coal into four jets.

PSD had a significant effect on NO_x levels when operating at high primary momentum flux. In general, finer PSD gave rise to lower NO_x values. Using a fine grind coal and a swirl number of 1.2, and gun position 150 mm produced a NO_x emission of 500 ppm. When using a coarse ground coal and the same values for gun position and swirl number, a NO_x value of 620 ppm was obtained. Clearly the momentum (M x V) of the larger particles is sufficient to penetrate the remote end of the IRZ and then mix with oxygen rich gases. This can be seen by the long flame lengths in photographs 3 and 4. PSD also had a strong influence on carbon burnout, as can be seen in Figure 4.8.

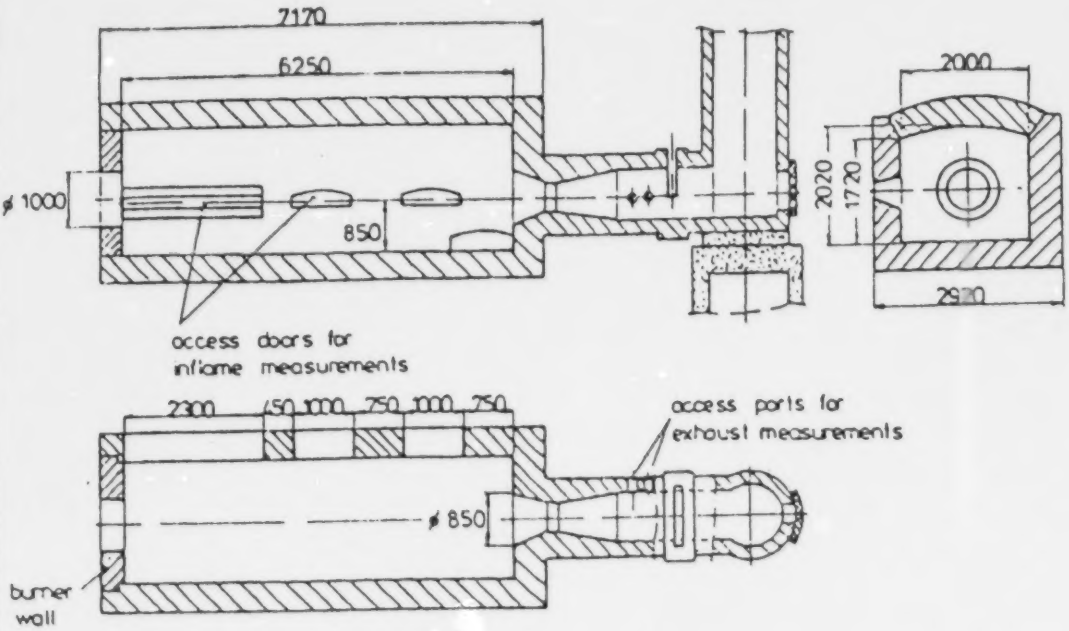
The influence of gun position on NO_x when operation at high momentum flux was much less than when operating at low momentum flux. The predicted NO_x levels using equation 3.4, (Report p.7), would decrease by 230 ppm for a swirl number of 1.2, and normal coal when the gun position changed from 0 mm to 150 mm.

Swirl level had a significant effect on NO_x emissions. The NO_x emission decreased from 610 ppm for Flame 60 to 420 ppm for Flame 59 as swirl was decreased from 1.7 to 0.7. This effect may be attributed to increased mixing of the coal jet with recirculated oxygen rich gas products at high swirl levels.

For Gun C, operated at a high momentum flux, the optimum NO_x emission obtained was 425 ppm. As shown in Photograph 6, Flame 59 was a jet type flame produced from fine grind coal at a swirl level of 0.7 and 75 mm gun position. However, the carbon in ash was 6.5%.

NO_x emission reduction could not be correlated with either primary air velocity or mass flow rate independently. The lack of correlation is shown in Figures 4.9 and 4.10. However, there was a correlation between the product of the two (momentum flux) and the

NO_x emissions as shown in Figure 4.11. For normal grind coal and swirl level of 0.9 - 1.2, primary air momentum flux had a similar effect on NO_x emissions at 0, 75 or 150 mm gun position.



- radiant zone firing density of 0,10 MW/m³ achieved by firing of 2,5 MW total thermal input
- 40% heat extraction achieved by 7 axisymmetric cooling loops

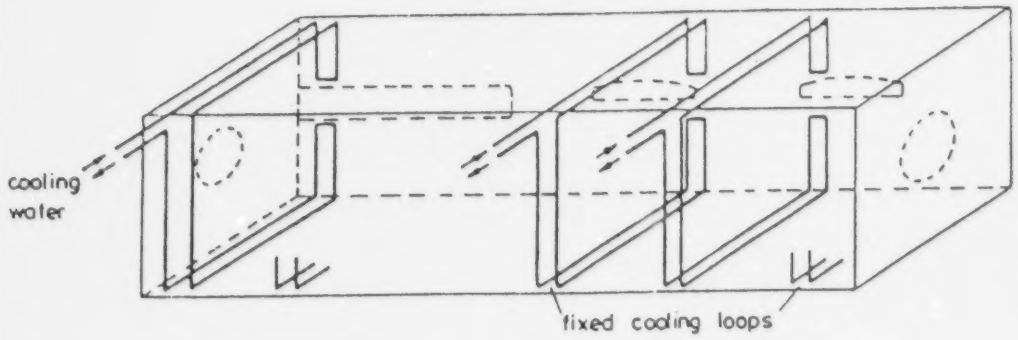


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Fig. 3.1 : IFRF semi-industrial scale furnace no:1 set up for large water tube boiler radiant zone simulation

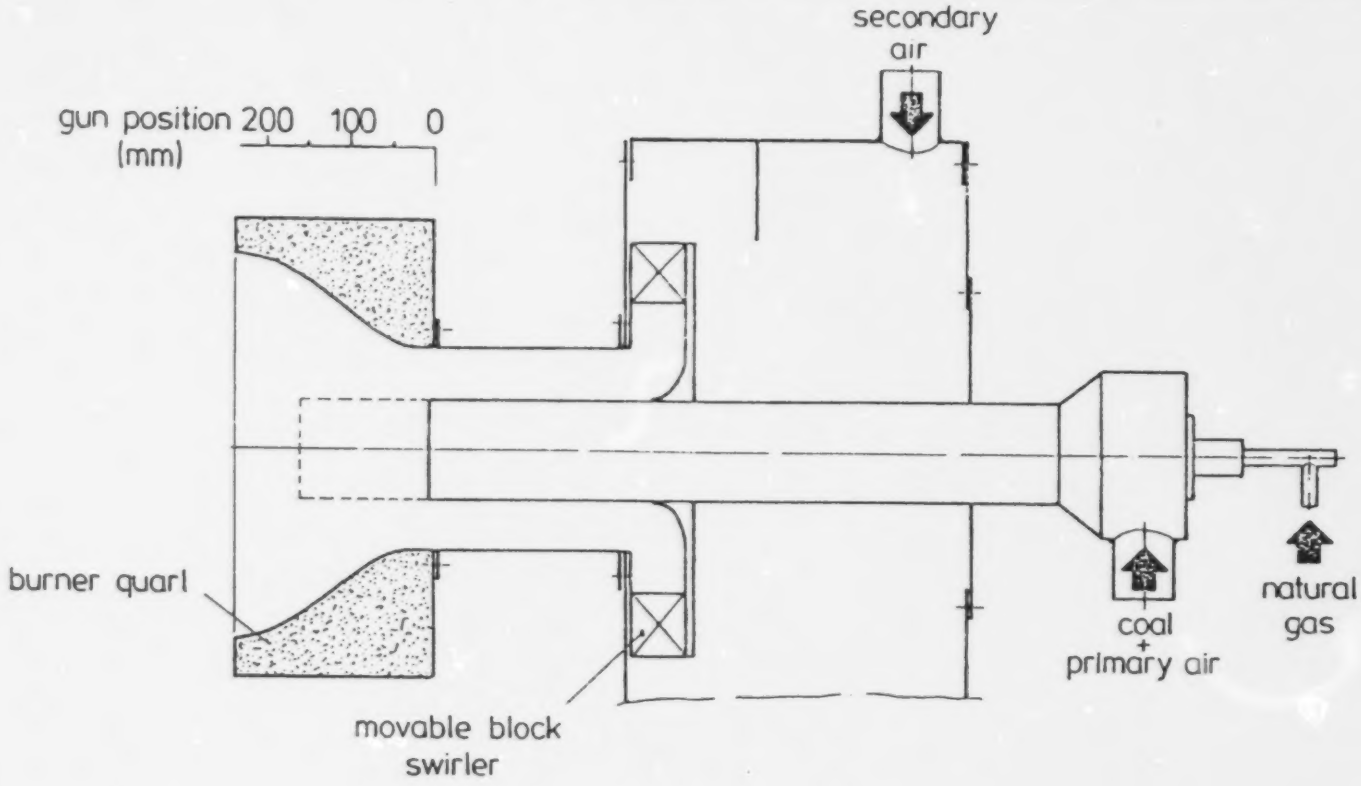

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Fig.3.2: Schematic of the aerodynamically air staged burner

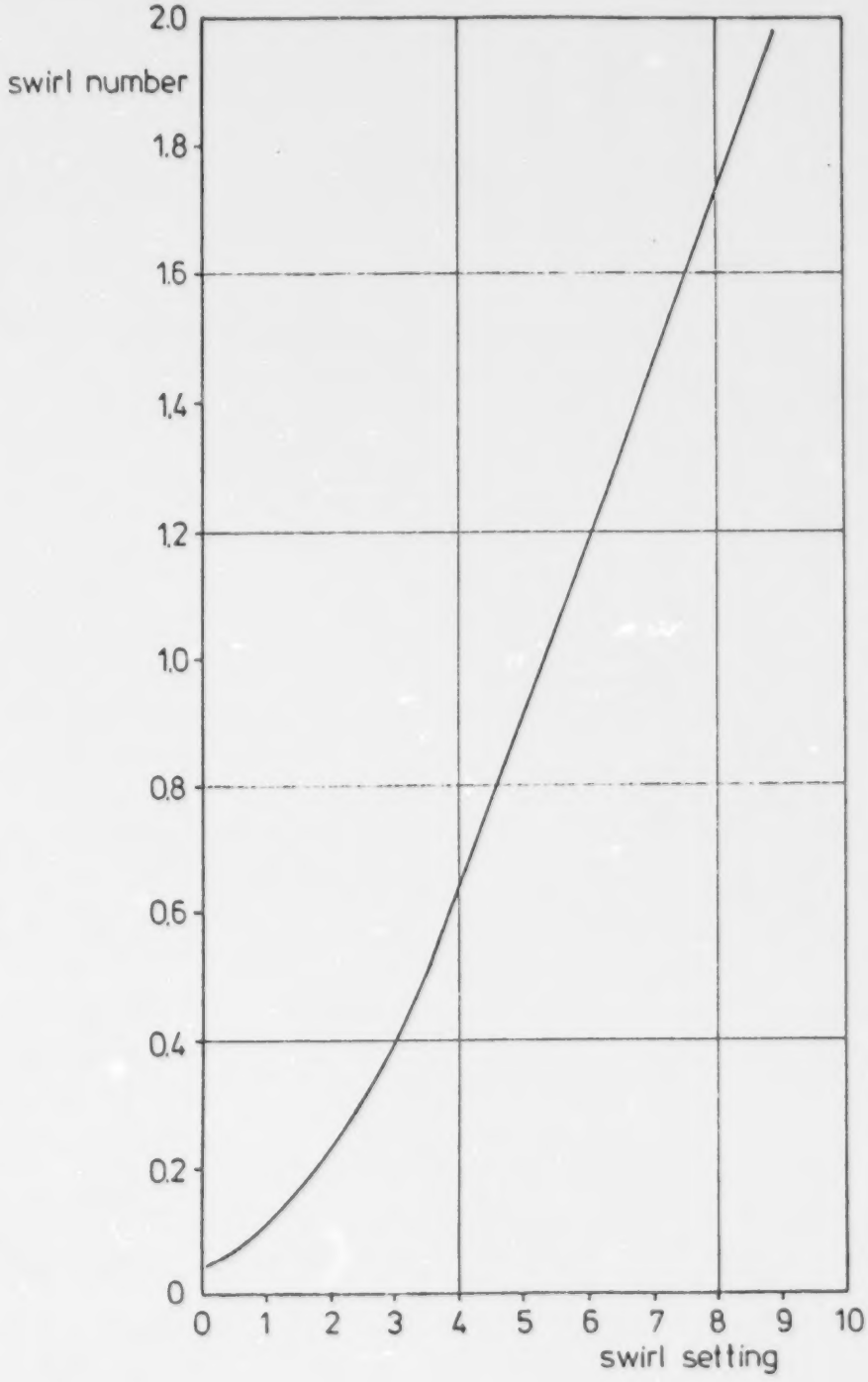

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Fig. 3.4: Effect of swirl block setting on swirl level

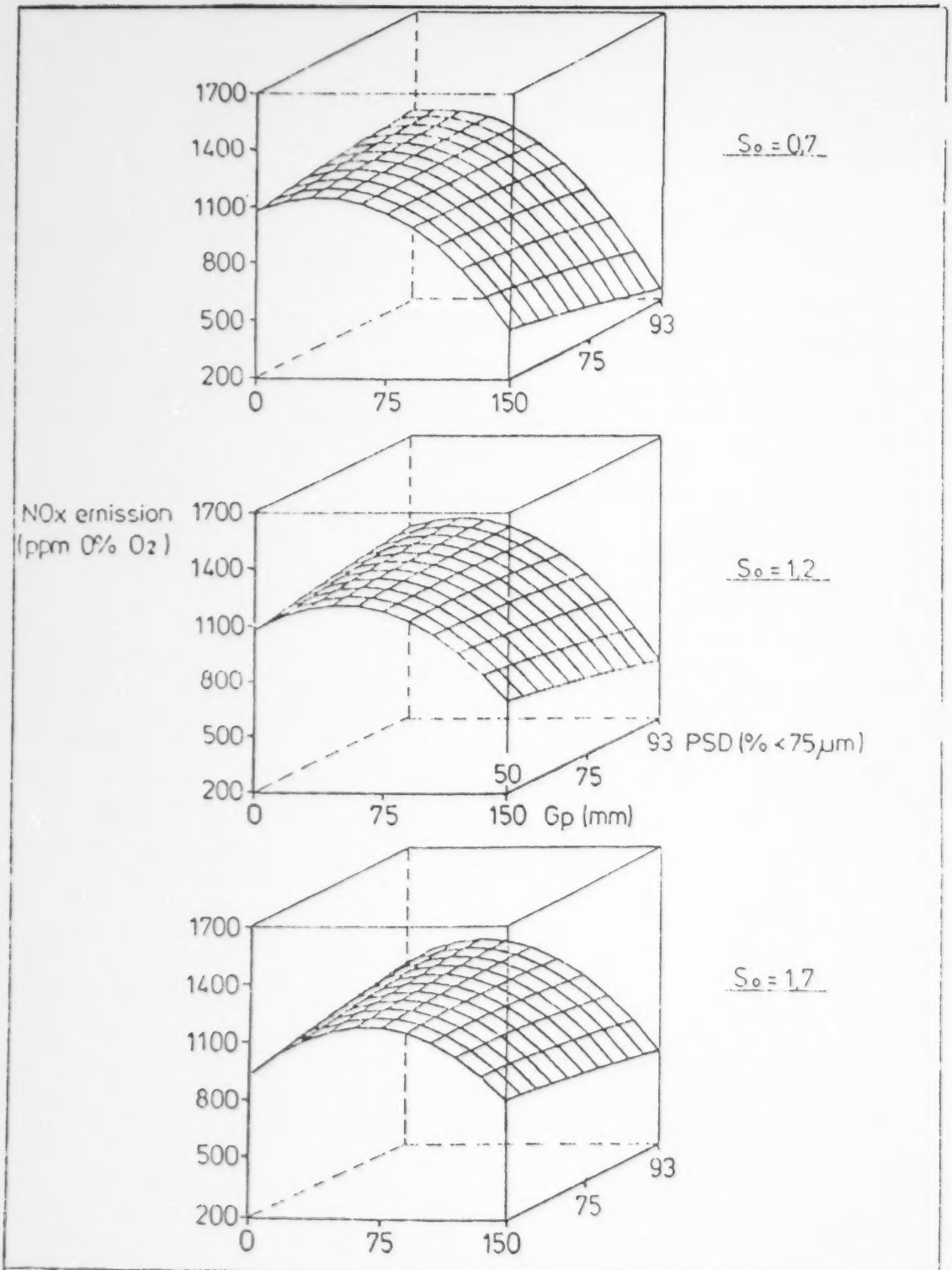

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Fig: 4.2 Effect of process parameters on NOx emissions for gun A

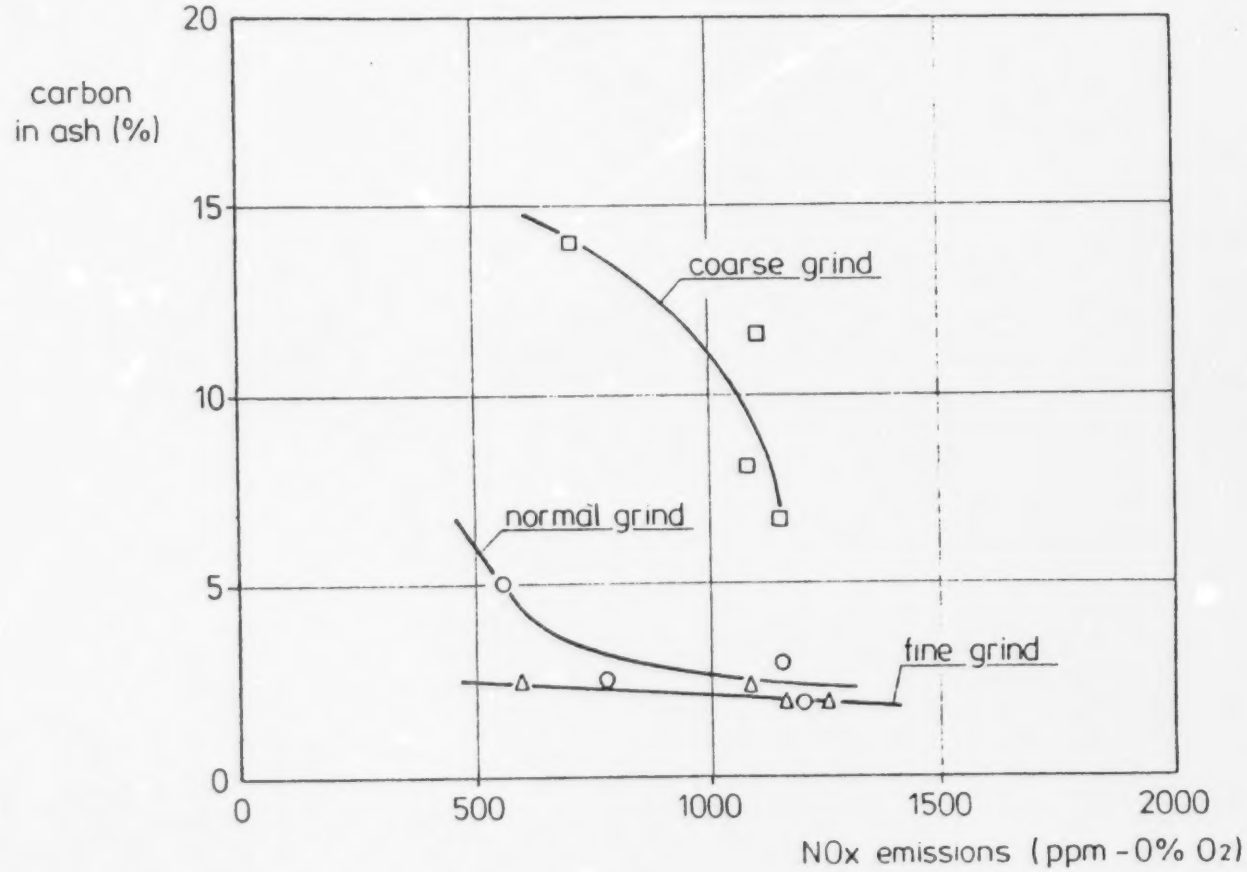

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Fig. 4.4: Relationship between NOx emissions and carbon in ash for gun A

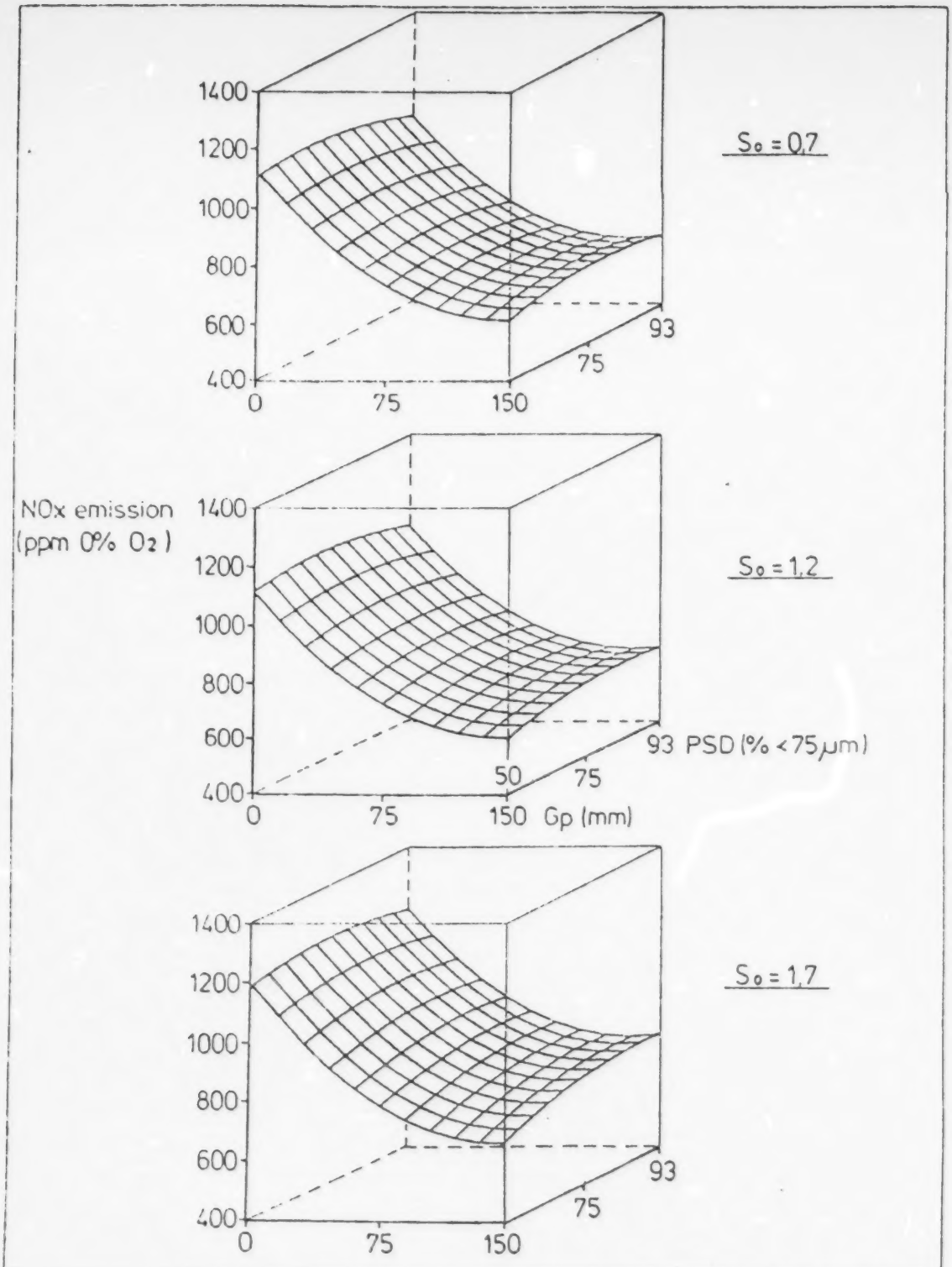

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Fig 4.5: Effect of process parameters on NOx emissions for gun C operated at a low air momentum flux

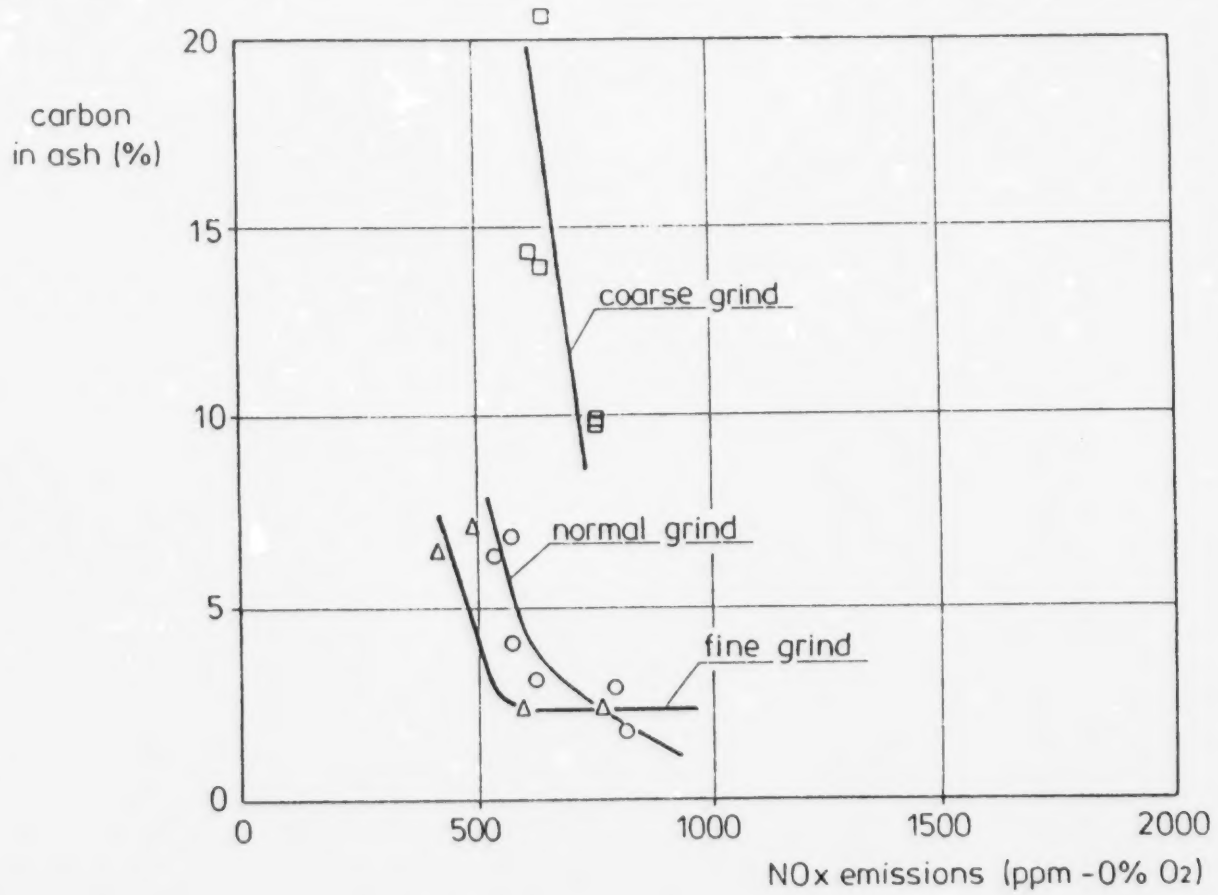

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Fig. 4.8: Relationship between NOx emissions and carbon in ash for gun C operated at a high air momentum flux

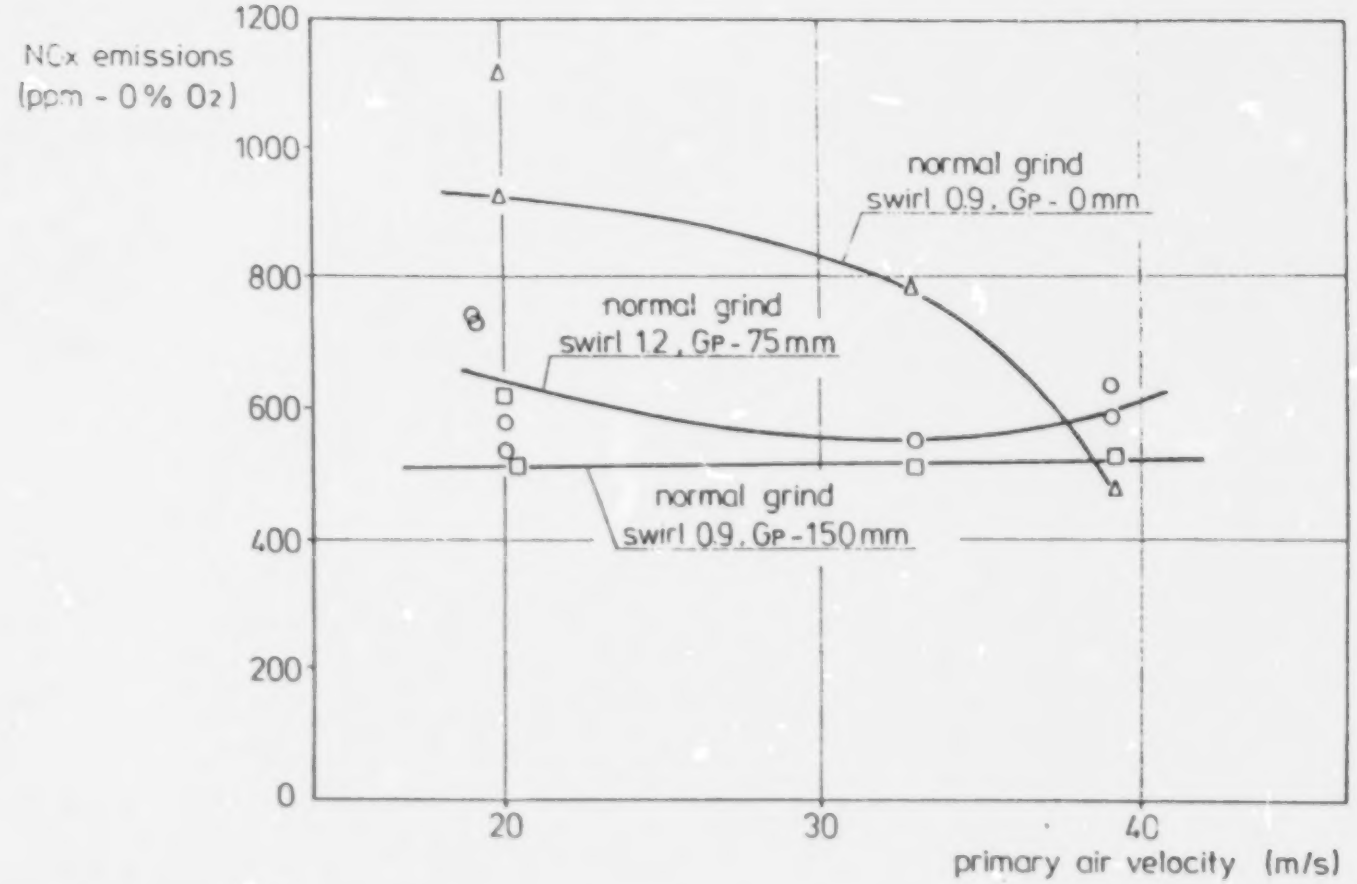

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Fig. 4.9: Effect of primary air velocity on NOx emissions

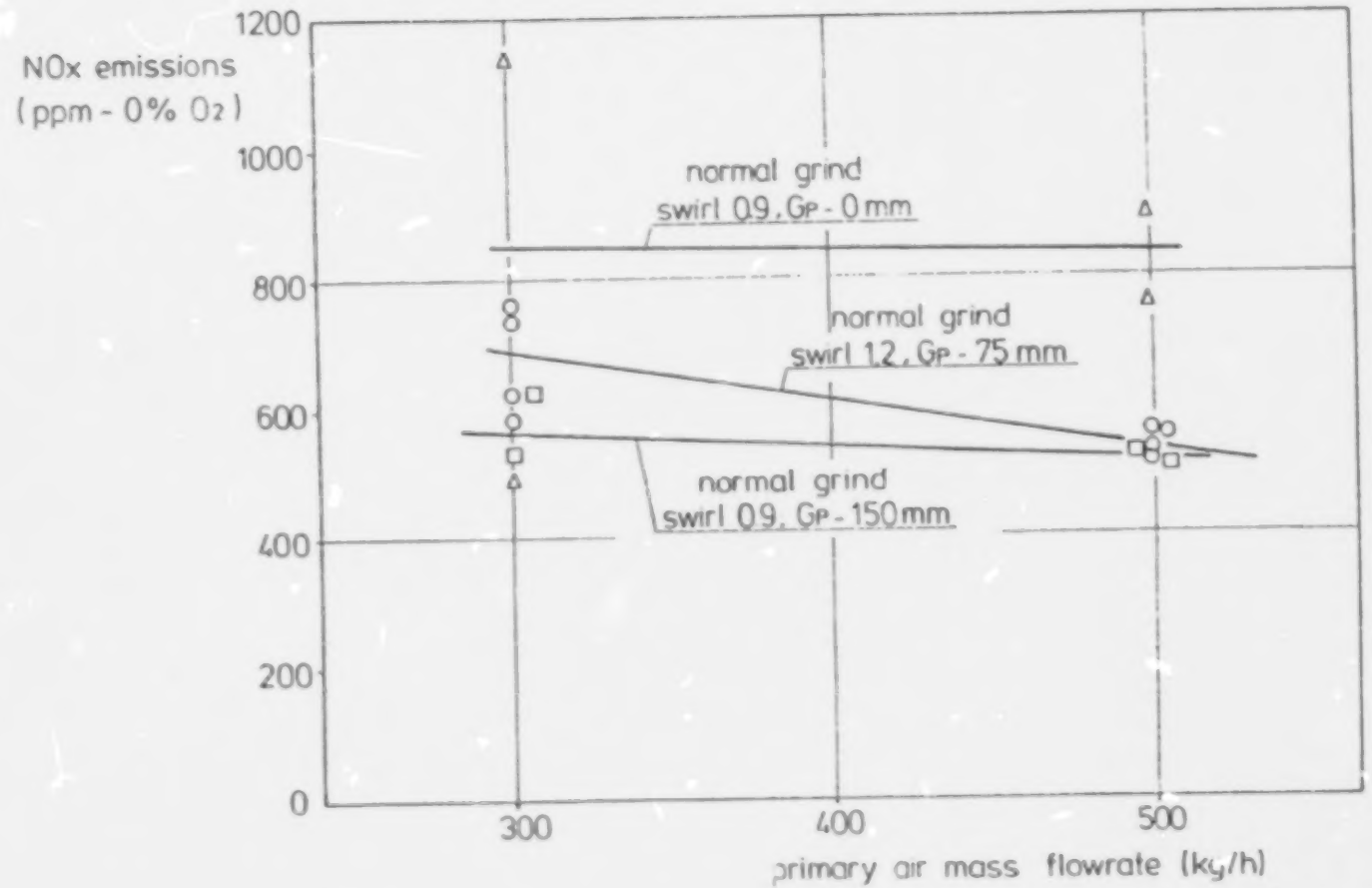

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Fig. 4.10: Effect of primary air mass flowrate on NOx emissions

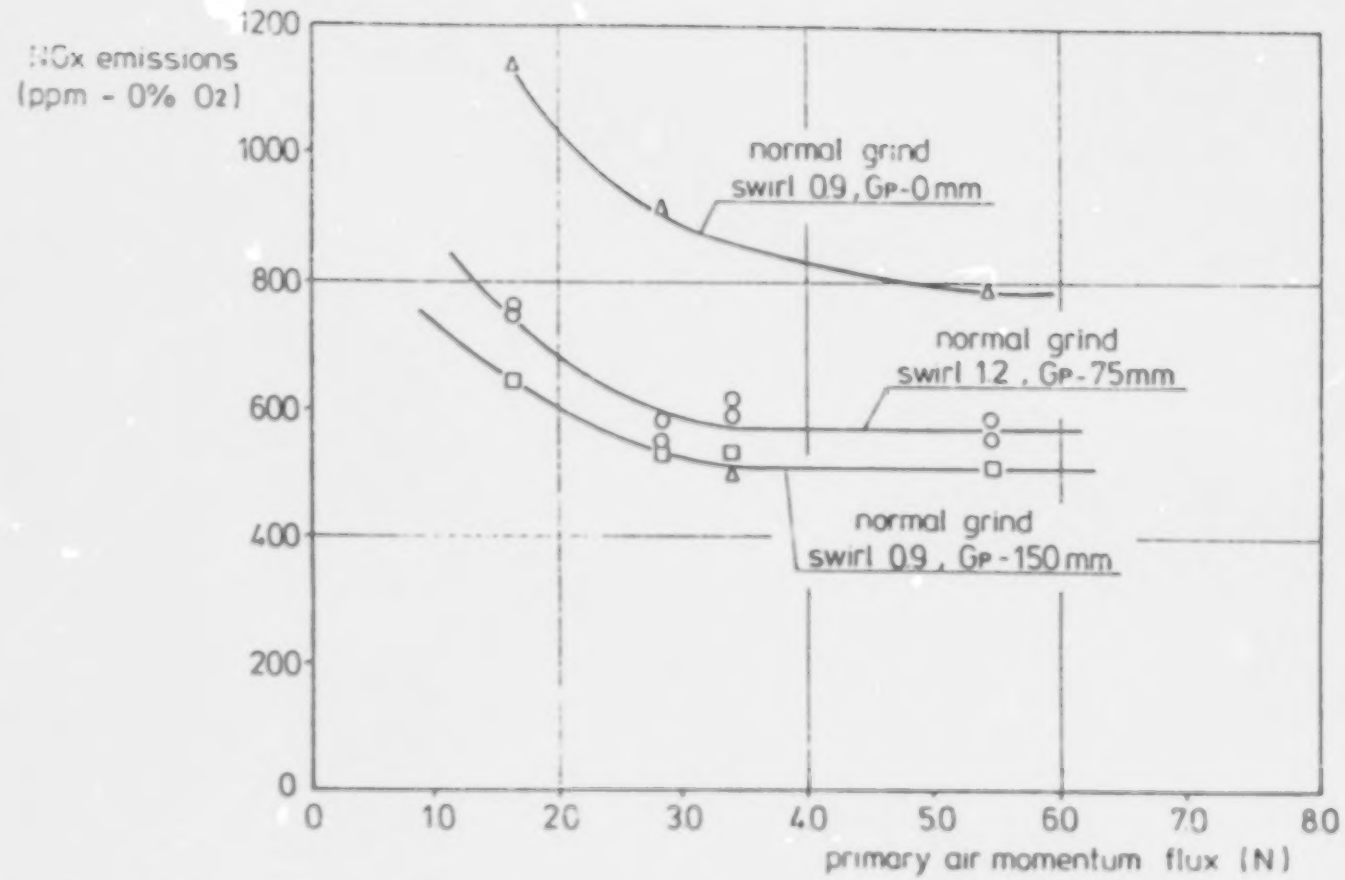

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Fig.4.11: Effect of primary air momentum flux on NOx emissions

3.0 REPORT NO. 5

DETAILED CHARACTERIZATION OF THE NEAR BURNER FIELD OF A LOW NO_x BURNER FIRING COAL OF TWO DIFFERENT RANKS Report on the CC 2-4 Experiments

1.0 OVERVIEW

The capabilities of the Aerodynamically Air Staged Burner (AASB) in burning pulverized coal with low NO_x emissions have been proven in previous studies. Very satisfactory results have been achieved, however, previous tests have concentrated on identifying the optimum combination of parameters, or "how" to make the burner provide the desired results. This study investigates the physical and chemical behaviour of the fuel and air flows in the near-burner field to provide further insight into "why" the burner is effective.

In the near-burner field, the interaction of fluid dynamics, particle flow paths, devolatilization rate and chemical reactions all contribute to a complex set of variables, which cause and effect are difficult to separate. By detailed sampling and analysis within the near-burner field and internal recirculation zone, it should be possible to determine the actual reactions taking place and to verify some of the explanations that have been put forth in earlier studies.

2.0 OBJECTIVES

The three objectives of this study were:

(a) To determine the thermal and chemical characteristics of the near-burner zones for two coals of different pyrolysis characteristics under baseline firing conditions. The lower-volatile coal would provide a relationship between volatility and the proportion of fuel nitrogen remaining in the char.

(b) To characterize the thermal and chemical environment of the near-burner zone for one of these coals under conditions of reduced NO_x emissions, for comparison with (a). This would verify the effectiveness of the mechanisms which separated the secondary air from the IRZ, and reactions in the various zones.

(c) To develop mathematical modelling of the particulate trajectories and to evaluate the predicted degree of penetration of the IRZ.

3.0 TEST PROCEDURE

A high-volatile bituminous coal, Scotts Branch, was tested in the AASB under "baseline" firing conditions (Flame #1), with the coal injector in the retracted position in the burner throat. The

baseline conditions were identical to those which produced relatively high NO_x levels on Scotts Branch coal in previous tests. Measurements were taken in the near-burner field to determine concentration contours of oxygen, CO, CO_2, NO_x, HCN and NH_3. Matrix measurements were also taken of temperature and particulate samples.

The procedure was then repeated (Flame #2) with Scotts Branch coal, with the injector extended 150 mm toward the quarl outlet. This provided the data to permit comparison of operating conditions for the "low NO_x" case. All previous measurements were duplicated.

Finally, a low-volatile coal, Peak Downs, was tested under the original "baseline" conditions (Flame #3). The low-volatile coal behaviour, particularly with regard to nitrogen release, was intended to allow comparison with the reactions of the previous test runs. Identical measurements were taken.

Mathematical modelling of particulate flow paths was performed with the use of the FLUENT computer program, which has been in use at the IFRF on other test programs. It is understood that the particle path tracking mode of the program was developed for the modelling of two phase flows in cyclone separators. The capabilities include turbulent flow, swirling flow, concurrent chemical reactions, eddy dissipation and radiation. All three flames were modelled.

4.0 SYNOPSIS OF TEST RESULTS

4.1 Flame Analyses

Thirty-four sample sets were taken during the three test runs. Their results, when plotted to show contours, provided an excellent graphical presentation of the locations of various intermediate reactions and the difference in performance of each flame type (Figures 5.1, 5.2, 5.3). In general, the results verified the chemical and physical interactions that had been surmised from previous tests.

Flame No.1 produced a flue gas NO_x level of 1226 ppm. The NO_x began forming within the burner quarl, and about 1000 ppm concentration was present at the quarl exit. HCN and NH_3 formation was concentrated on the IRZ boundary with the secondary air. The temperature in this area was 400 to 500°C.

Flue gas NO_x level was 495 ppm for Flame No. 2. The NO_x formation did not exceed 600 ppm at any point, and most of the formation was concentrated along the centreline of the IRZ. The formation of HCN was also heavily concentrated on the centreline, and peaked at about 1700 ppm, or about four times that of Flame No.1. The HCN concentration decreased from 1700 ppm to 200 ppm in the short space between 0.5 m and 0.9 m downstream of the burner exit. This 1500 ppm decrease in HCN resulted in only a 200 ppm increase in NO_x. A rapid increase in gas temperature was also noted in this interval.

Flame No. 3 gave a NO_x reading of 640 ppm at the furnace exit, and carbon burnout was only 91 percent (cf. 99%+ for Flame Nos. 1&2). Flow patterns and reactions were generally similar to Flame No.1. The exception was the slower release of nitrogen from the coal, and the greater proportion retained in the char.

4.2 Particle Trajectories

Particle trajectories were modelled with the coal injector in two positions, as for Flame Nos. 1 and 2. In each case, two sizes of particles were plotted: 40 micron and 110 micron. For the retracted injector case, the model showed that the smaller particles were immediately entrained in the secondary air flow. The larger particles penetrated the IRZ, but were soon deflected outward from the IRZ envelope. Model calculations showed that more than 90 percent of the devolatilization occurred within the secondary air flow.

The same procedure with the injector extended to 150 mm produced quite different results. In this case all the particles penetrated the IRZ, with some not encountering secondary air until past the IRZ downstream boundary. The model predicted that over 70 percent of the volatile products were released within the IRZ. Also, particle diameter had less effect on the trajectory than in Flame No.1.

5.0 REPORT CONCLUSIONS

With the extensive scope of this study, many observations pertinent to the operation of the AASB emerged throughout the text. Some of these items, which are effectively conclusions, found their way into the "Results and Discussions" section, and are summarized here along with the tabulated conclusions.

1. In the high-NO_x Flame No.1, the majority of coal particles devolatized in a narrow range on the interface between the IRZ and the forward flowing secondary air.

2. In the low-NO_x Flame No. 2, delayed mixing of the coal and secondary air prevented oxidation of the volatile nitrogen species. Lower temperatures in the regions of HCN release resulted in limited conversion to NO species. Nitrogen reduction reactions leading to N_2 dominated in this region of the flame.

3. The release of nitrogen is believed to precede other volatile components in the initial stage of pyrolysis.

4. With the coal injector at the burner throat, the mathematical model of fine particles showed them to be rapidly entrained in the secondary air flow. Larger particles, when confronted by the IRZ, were deflected outward, with limited time exposure to the oxygen-lean combustion products.

5. With the coal injector extended to 0.65 quarl lengths beyond the throat, most of the coal penetrated the oxygen-lean IRZ.

6.0 COMMENTARY

This study illuminates several important operating characteristics of the AASB, and is particularly successful in identifying the differences in flame chemistry between the low-NO_x (extended) and high NO_x (retracted) burner positions. The detailed sampling maps provide quantifiable performance figures which can be directly related to "baseline firing conditions" in previous tests. Mathematical modelling of the coal particle trajectories provides further vindication for the concept that coal particle penetration of the IRZ is fundamental to the suppression of NO_x formation. The objectives of the study seem to have been fulfilled in all respects.

Some emphasis is placed on the effect of "the super-sub critical flow transition..." of the secondary air (Report Section 2.), and its influence on the location of the IRZ. It is not entirely clear what type of transition this is, and how it affects the secondary air flow pattern. If the location of this transition is critical to the burner performance, could it limit the turn-down ratio, or require very sensitive air control in a utility-scale burner?

In Flame No.1 of the high-volatile Scotts Branch test, the very thorough analyses of near burner field components shows most of the coal devolatilization to occur in a narrow region between the primary and secondary air streams. This does not appear to be a high temperature location, and the question arises as to the reason for the rapid release of volatiles at this particular point. It may be a coincidental function of trajectory length and residence time. The same sort of pattern emerges, with lesser intensity, in the low-volatile Peak Downs Flame No. 3. As this is the primary source of HCN and NH_3 leading to the high NO_x formation in Flame No.1, it may be worthwhile to further investigate this aspect.

A preliminary assessment of the AASB effectiveness with low-volatile coal suggests that staged combustion benefits are mainly due to the lower flame temperatures, and not to the controlled devolatilization. Should this prove valid, the incentive for commercial development may be inhibited. However, fuel related aspects are studied in detail in Report No. 6. The only other notable item regarding Peak Downs coal was the low carbon burnout (T_x) of 91 percent. No explanation is offered for this, presum-ably as it is not directly related to the near burner field performance.

An actual sieve analysis of the as-burnt fuel would have permitted comparison of the particle size range and distribution to the assumed particle sizes in the mathematical model.

The combustion zone chemical analysis also detected the presence and location of secondary pyrolysis products in the form of nitrogen-containing tars. This appears to be an important contribution to the direction of future research in the study of volatization and NO_x formation.

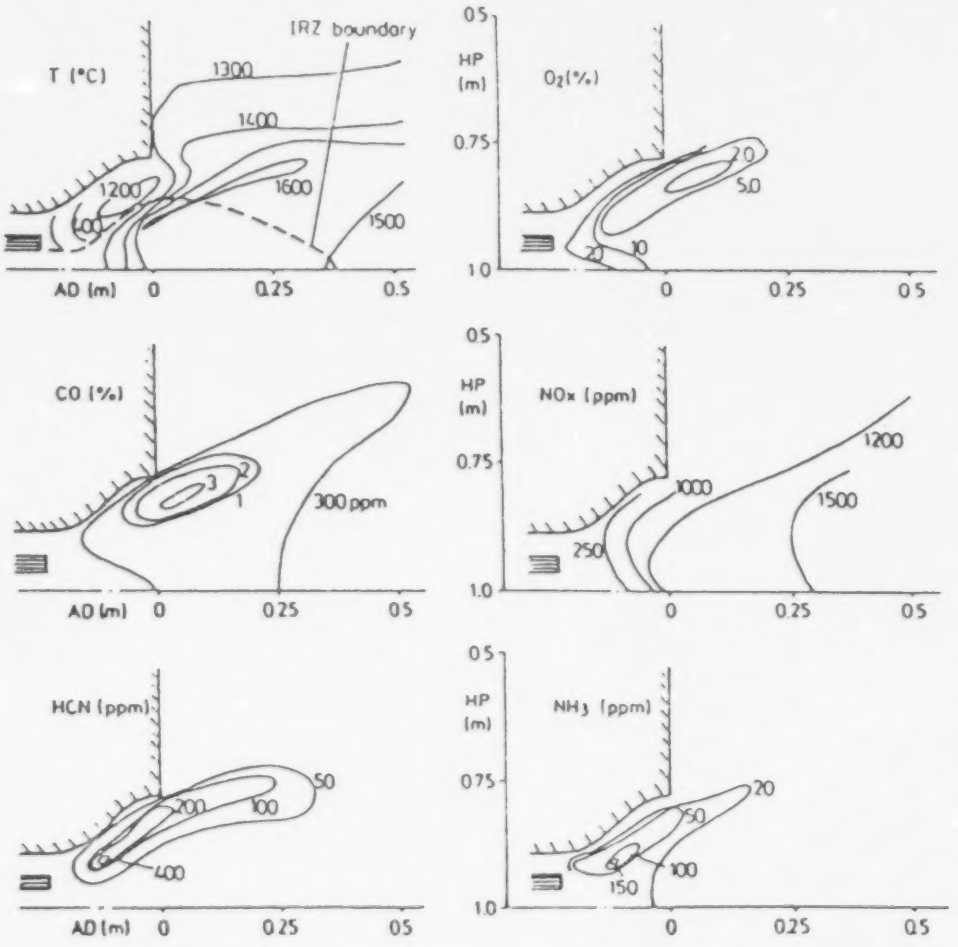

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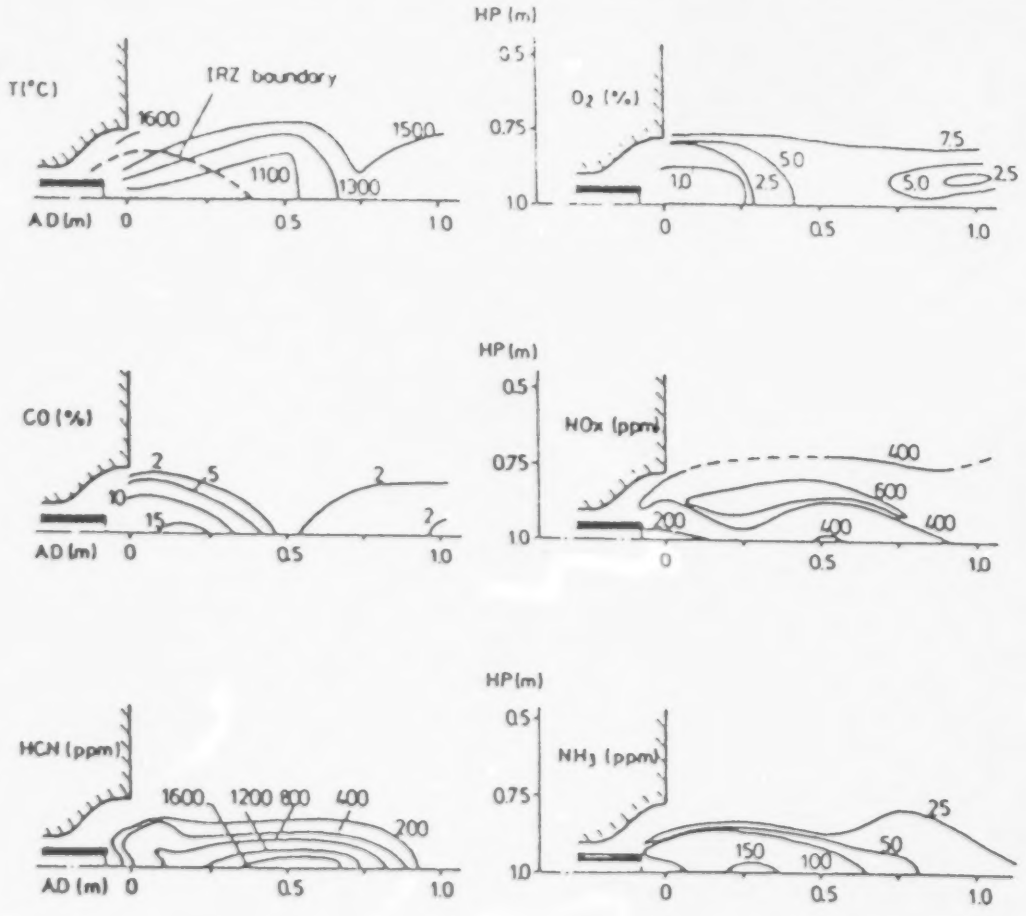
Fig. 5.1: In-flame isolines SCOTTS BRANCH coal injector at 0



FLAME 4.2

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Fig. 5.2 : In-flame isolines SCOTTS BRANCH coal injector at +150mm (0.65 quarl length)

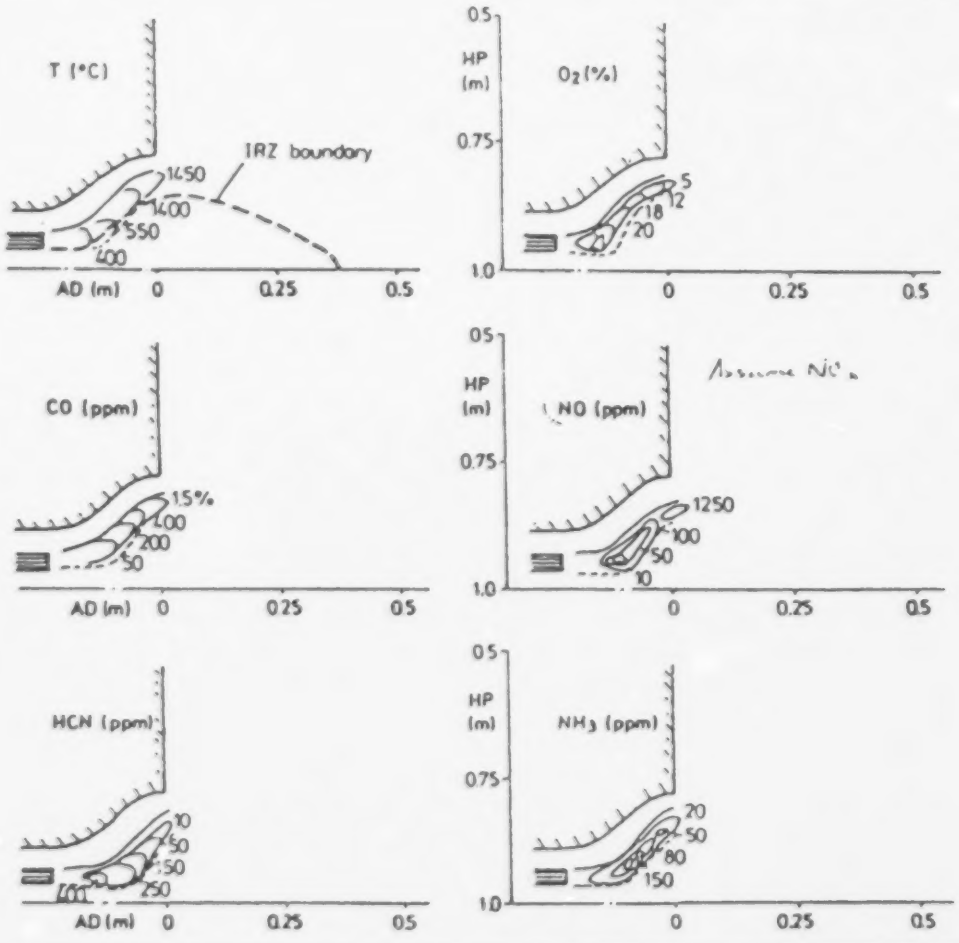

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Fig. 5.3: In-flame isolines PEAK DOWN coal injector at 0

FLAME #3

3.0 REPORT NO. 6

EFFECT OF COAL QUALITY ON THE PERFORMANCE OF LOW NO_x BURNERS Report of the CC 3 Investigation

1.0 OVERVIEW

Up to this point, testing of the AASB had been confined primarily to coals possessing properties which were believed to be either distinctly favourable to air staged NO_x reduction (Scotts Branch), or of marginal susceptibility to improvement (Heinrich Robert). Within this discrete range of coal properties, the aerodynamically air staged burner (AASB), air staged precombustor burner (ASPB) and externally air staged burner (EASB) were tested at length to: (a) determine the optimum combination of operating parameters and (b) identify which of these factors had the greatest influence in reducing NO_x formation.

This study was conceived to expand the previously achieved success in NO_x reduction to include coals with a wider range of characteristics. The objective was to collect a data base of test results which would permit the development of correlations between fuel properties and potential NO_x reduction with the AASB. By this means, the potential performance of the AASB might be more confidently predicted for coals of many other origins. Clearly, this is seen to be the next logical step in the commercial development of the AASB.

The two new authors enlisted for this study do not appear to have had the opportunity to participate in the previous AASB studies. Recognizing that the current report is a "stand alone" document, it must be observed that a considerable proportion of the contained discussion is a reiteration of principles developed in the earlier works.

An interesting development in this study is the introduction of work performed by these same authors on the Isothermal Plug Flow Reactor (IPFR). This IFRF work had apparently been proceeding independently from, but in parallel with the AASB studies. The reactor simulates, on a laboratory scale, the primary pyrolysis reactions in a pulverized coal flame. The resulting information on the quantity and composition of volatile matter released appears to be a valuable contribution to the explanation of the reaction phenomena observed in this and previous AASB tests.

2.0 OBJECTIVES

The objectives of this study were to:

(a) Determine the effect of primary coal characteristics (eg. % volatile matter, % nitrogen) on the NO_x reduction and carbon burnout performance of the AASB

(b) Compare the test results of the AASB with those of the EASB, as a means of predicting commercial applicability

(c) Incorporate the results of a separate study on the Isothermal Plug Flow Reactor (IPFR) to determine the actual pulverized coal devolatilization effects, as they relate to the performance of the AASB

(d) Develop, from (a) and (c), correlations of coal properties with AASB burner performance

3.0 TEST PROCEDURE

Burner tests were performed on three new coals, and the results were compared with the optimum for Heinrich Robert and Scotts Branch coals used in Report #2. Results for this study thus incorporate the following range of coal characteristics:

		Prox. Anal*		Ultimate Analysis*					LCV
		VM	Ash	C	H	O	S	N	(MJ/kg)
Hugo	MVB	25.7	8.2	88.5	5.0	4.2	0.7	1.7	35.2
Heinrich Robert	MVB	25.7	6.0	87.9	4.9	5.3	0.9	1.7	34.8
Scotts Branch	HVB	36.8	5.6	81.4	5.1	10.2	0.8	1.7	33.8
Coal Valley	HVB	44.1	9.7	75.7	4.8	18.1	0.4	1.0	30.7
Rhein Braun	LIG	55.3	5.7	65.9	4.9	27.6	0.8	0.8	23.5

* Percent DAF

Tests were carried out in IFRF Furnace No.1, with essentially the same AASB combustion parameters as for Report #2, in order to utilize the previous results. Furnace cooling loops were also in identical positions. Primary air was maintained at 70°C and about 15 m/s velocity. Secondary air was heated to 300°C and the velocity range was 40 to 45 m/s. An overall stoichiometry of 1.15 was maintained. Two parameters: swirl level and injector position, were adjusted in order to ensure the burner performance was reasonably optimized for each particular coal.

In total, 61 test runs were made on the three coal samples. During each of these test runs, in-flame measurements were taken to determine:

- Gas Temperature
- Flame Flow Pattern
- Concentrations of NO_x, O_2, CO, CO_2

In addition, flue gas sampling was conducted to determine carbon burn-out, furnace gas exit temperature and overall NO_x levels.

4.0 SYNOPSIS OF TEST RESULTS

4.1 General

Some of the results obtained in this test contrasted with those of Report #2 which it was meant to extend. Most noticeable was the distinct transition from the high-NO_x type II flame to the low-NO_x type I flame (IRZ penetrating) as the fuel injector was extended toward the quarl opening. The transition was observed to occur at gun positions between 0 and +40 mm. Within this span, it appeared to be possible to achieve either type of flame. Throughout most of the tests, a swirl number of 0.6 was maintained. Results indicated that swirl number had less effect on the flame type and NO_x level than the position of the injector gun.

A reduction in NO_x formation of between 30 and 50 percent was recorded through the transition from type II to type I flames for the coals tested. It had been anticipated that the reduction would be proportional to the volatile matter content of the coal. However, the following table indicates that the correlation was indefinite. For this purpose, the volatile matter used was that derived from the Isothermal Plug Flow Reactor tests, as these are believed to more closely approximate the actual in-flame conditions than the more widely recognized proximate analysis volatile matter index.

TABLE 5.2 - Effect of Coal Quality on AASB Performance (IFRF Report No. F 08/a/9)

	VM % (IPFR)	%Nvm	NO_{xun} (ppm)	NO_{xst} (ppm)	%Red
Hugo	39	2.2	520	350	33
Heinrich Robert	44	2.2	700	500	29
Scotts Branch	64	1.7	900	425	53
Coal Valley	83	1.0	940	490	48
Rhein Braun	91	0.8	960	490	49

4.2 Effect of Coal Quality

This table shows the expected trend in the relationship between volatile matter and unstaged NO_x formation. However, NO_x formation in the staged combustion case does not appear to correlate with the selected coal characteristics. Some discussion is offered on the relative strength of the influences of quantity of volatile matter released (VM%) and its nitrogen content (%Nvm).

4.3 Carbon Burnout

The Report Table 5.3 clearly indicates that carbon burnout is unaffected by air staging, but increases with decreasing coal rank. It is further pointed out that the observed range of carbon burnout substantially exceeds the Furnace No. 1 residence time distribution reported in a previous study. This was interpreted as confirmation that the residence time for Furnace No. 1 did not preclude its use in predicting coal burnout in larger scale furnaces.

4.4 Comparison of AASB and EASB Performance

A comparison of AASB and EASB performances was undertaken, based on previous test results for the EASB. The results clearly indicated that one coal, Heinrich Robert, achieved greater NO_x reduction in the EASB than in the AASB. On the other hand, Scotts Branch exhibited similar NO_x levels with each burner. The exceedingly good EASB performance with Heinrich Robert (MV) was explained in terms of a speculated difference in primary zone stoichiometry from that for Scotts Branch (HV). By this explanation, the medium volatile coals are exposed to an overall fuel-lean condition in the primary zone, while the high volatile fuels experience a fuel-rich atmosphere. This variation results in lower staged NO_x formation for coals with higher volatile fractions.

4.5 Detailed Flame Measurements

Measurements were performed as outlined in Section 3.0. The high gradients and unsteady conditions in the near-burner zone made interpretation of results difficult. The Report recognizes that "...A complete description of the phenomena...requires a much larger data base than the one taken in this study,..."

A comparison of centreline flame temperature profiles shows the effect of the release of volatiles and moisture:

		Quarl Exit	Exit + 50 cm
Hugo	MVB	1600°C	1500°C
Coal Valley	HVB	1040°C	1490°C
Rhein Braun	LIG	360°C	1470°C

The explanation provided is that, in passing through the IRZ, Hugo, with a lower release of volatiles, reaches combustible stoichiometry based on volatiles more rapidly than the other fuels.

5.0 REPORT CONCLUSIONS

General

1. The overall performance of the AASB was similar to that found in previous trials.

2. Flue NO_x emissions can be controlled by insertion of the coal gun, which changes the trajectories of the coal particles.

3. Swirl has little effect on NO_x emissions.

4. Both Type I and Type II flames can exist under the same stable conditions. No intermediate flame types or NO_x values were observed.

Coal Quality

5. For high NO_x (unstaged) flames, as volatile matter and VM nitrogen content rise, NO_x emissions rise.

6. For low NO_x (staged) flames, the narrow range of NO_x levels make any correlation with fuel characteristics difficult.

Burner Performance

7. Carbon burnout is not significantly affected by air staging for any of the coals tested.

8. Both the AASB and EASB produce similar NO_x emission levels.

9. Staged NO_x emissions are a strong function of burner design and operation, as well as coal quality.

10. When analyzing a wide range of coals for the effects of coal quality, the burner must be tuned for each individual coal. Otherwise, results may be misleading.

6.0 COMMENTARY

The most conspicuous feature of this study is the zealous objectives that were established for it. The customary development for research of this nature seems to follow two discrete stages: an overview assessment to identify the most sensitive variables and their ranges, followed by a detailed investigation to explain the observations or determine the most advantageous combination. In contrast, Report #6 adopts "optimum" AASB settings from Report #2, fuel characteristics refinements from the Plug Flow Reactor study, and proceeds to engage both the above stages simultaneously. Specifically, the superposition of detailed in-flame mapping upon the evaluation of the overall burner performance with a variety of coals may have been ambitious.

In order to incorporate Report #2 results, this study duplicated the AASB variables previously found to give low NO_x formation with Scotts Branch and Heinrich Robert coals. Principally, these were: primary air velocity and temperature, secondary air temperature, swirl index (limited in range) and furnace heat extraction loop locations. In fact, the primary air velocity selected (15 m/s) was 15 percent or more below the optimum velocities from Report #2. As the particle momentum is an important factor in achieving penetration of the IRZ, this may have had an influence on the NO_x reductions achieved. These reductions did not seem to be as pronounced as in earlier tests.

Burner test results identified an unexpectedly abrupt transition from the "unstaged" conventional (high NO_x) type II flame configuration to the aerodynamically staged low NO_x type I flame performance. Contrary to earlier studies, it seems that a transition zone exists for gun positions between 0 and 40 mm extension, in which either type of flame can be maintained. This may result from the limited ranges

of secondary air flow and swirl numbers permitted. It is probably significant that the authors conclude that it is impractical to compare the relative performances of different coals with a single set of AASB operating parameters.

Many useful facts were presented on NO_x formation in general and on the AASB in particular. The operating temperature of the coal injector tip when in the extended position could seriously reduce its longevity. A facet of this study was the measurement of burner tip temperatures under operating conditions. These were found not to exceed 250°C which, with the 316 TI stainless steel injector material employed, should give satisfactory service.

Unfortunately, the primary purpose of the study "to assess the effect of coal quality on the performance of the (staged) AASB" did not produce a convincing correlation. This was in spite of extensive attempts to discover a combination of coal characteristics such as volatile matter, oxygen content, nitrogen distribution between volatiles and char, and so forth, which might correlate with the overall NO_x level in the flue gas.

In several places the Report makes passing reference to the fact that the Externally Air Staged Burner achieved better results following scale-up to industrial applications than it had in the test furnace. Furthermore, a comparison of the EASB and AASB performances is synthesized on the basis of earlier test results. The Report concludes that the AASB NO_x reduction potential is similar to that for the EASB, although an element of objectivity may be perceived in the arguments presented.

In all, this Report contains the most thorough coverage of the general topic of NO_x formation of the IFRF studies reviewed.

3.0 REPORT NO. 7

THE EFFECT OF SCALE ON THE PERFORMANCE OF THE AERODYNAMICALLY AIR STAGED BURNER
Report on the AP 17 Experiments

1.0 OVERVIEW

The ultimate objective of the IFRF series of studies is the development of an industrial or utility scale AAS burner which will be commercially viable for either new construction or retrofit applications. As for most model-to-prototype development programs, this imposes the need for a technique to scale-up performance predictions accompanied by an appropriate degree of confidence.

At least one boiler manufacturer, Steinmueller GmbH, has developed a full scale EASB from a 2.5 MW_t test burner developed at the IFRF. Firing Saar HVB coal, the reduction in NO_x formation with increasing burner size was well documented. This report relates that Steinmueller scaled up the test burner, (12:1 and later 27:1) based on constant velocity criteria. However, there appears to be no universally accepted method for dimensionally scaling up burners in order to ensure the similitude necessary for accurate performance prediction.

Previous reports (e.g. Report #6) have referred to the experience gained in testing the prototype EASB, and the fact that NO_x formation in the full scale burner "decreased... as the scale increased." It was suggested that the same trend could be safely predicted with the AASB.

Although IFRF Furnace No. 1 is limited to a heat release rate considerably below those for typical industrial burners, it was felt that a sufficient range of scale could be achieved within this furnace to permit prediction of the initial trends in performance with an increase in burner size.

Thus Report #7 was initiated to investigate the effects of scale on the performance of the AASB. It is of interest that the only fuel used for combustion testing of this important aspect was Coal Valley coal from Alberta.

2.0 OBJECTIVES

After extensive discussion of the various criteria and techniques for scaling burner designs, and predicting scaled-up performance, the objectives of this study emerged as:

- to evaluate the effect on the properties of the near burner field, and specifically NO_x formation, of employing the combination of (a) constant velocity scaling with (b) geometric similarity in the scaling up of the AASB design between 1.0 and 4.0 MW_t.

3.0 TEST PROCEDURE

3.1 General

Three experimental AASB burners were designed and built for nominal inputs of 1.0, 2.5 and 4.0 MW_t. These burners were used in IFRF Furnace No. 1, which was essentially identical in heat absorbtion profile for all tests.

Two flame patterns, Type II (high NO_x) and Type I (low NO_x), were generated for each burner size. This was achieved by positioning the coal injector guns at two points: (a) burner throat and (b) injector inserted 0.4 m throat diameter into the quarl for each burner size.

Burner designs were scaled down and up from the 2.5 MW_t AASB used in previous trials. Dimensional proportions were kept in the same ratio (e.g. quarl length/diameter), and air stream velocities, momentum flux rations and swirl numbers were kept constant for all three burners.

Trials were begun with the 4.0 MW_t burner. With each successive change to a smaller burner, furnace cooling loops were removed in the vicinity of the volatile flame length in order to achieve a constant burner zone heat liberation rate. Excess air was kept constant at 20 percent of all test runs.

3.2 Measurements Taken

For each of the six test runs, both flame zone matrix measurements and flue gas furnace exit measurements were taken. The in-flame measurements included temperature, NO_x, O_2, CO, CO_2 and solids concentration. Furnace exit measured conditions were temperature, gas composition and carbon burnout.

4.0 SYNOPSIS OF TEST RESULTS

An apparent disparity between the specified and actual coal analyses caused the burner designs to be somewhat undersized, resulting in achieved thermal capacities of 3.4, 2.2 and 0.9 MW_t (cf. 4.0, 2.5, 1.0 expected). However, the scale range of about 1.4 was maintained.

Furnace exit measurements showed that for the three "baseline" cases (Type II flame), NO_x formation increased about 12 percent with burner size. For the Type I "staged" flames, NO_x levels generally decreased about 16 percent with the same increase in burner size.

Good correlations were obtained between flame length and burner heat release rates for both Type I and Type II flames:

Type I	$F.L. = 1.03Q^{0.4}$
Type II	$F.L. = 0.63Q^{0.5}$

In all cases the estimated total flame length were proportional to the burner characteristic dimensions. Furthermore, it can be seen from the above relationship that the type I staged flame becomes progressively shorter, relative to the Type II flame as burner size increases, i.e.

$$\frac{\text{F.L. Type I}}{\text{F.L. Type II}} = \frac{(1.03Q)^{0.4}}{(0.63Q)^{0.5}} = \frac{1.63}{(Q)^{0.1}}$$

Carbon burnout is unrelated to burner size.

The axial dimension of the IRZ is typically $3xD_o$ (burner throat diameter) for all burner sizes. This means in the case of the AASB, the IRZ extends about 2 D_o outside the burner quarl exit plane.

5.0 REPORT CONCLUSIONS

1. The interpretation of scaling data (for this report) was complex, and small differences in measured flame conditions could have a significant effect on the performance of a larger scale burner.

2. In the baseline (high NO_x) flames, ignition occurred well back in the quarl, with the flame front propagating radially.

3. For baseline (Type II) flames, NO_x production increased with burner size.

4. A coal injector extension of 0.4 burner throat diameters (D_o) resulted in the coal jet penetrating the IRZ for all burner sizes, this producing low NO_x (Type I) flames.

5. With Type I flames, significant devolatilization occurred within the oxygen deficient IRZ.

6. NO_x emissions with the Type I flames were substantially lower than the Type II flames for all burner sizes. NO_x emissions tended to decrease with increasing burner size.

7. The combination of constant velocity scaling and geometric similarity appears to result in similar aerodynamic and flame structural features for burners of varying sizes. However, differences are noted in gas composition and temperature distribution.

8. Constant velocity scaling gives reasonable results in the prediction of AASB performance.

6.0 COMMENTARY

With the stated objective of developing criteria for scaling-up the AASB to industrial capacity, this report might be considered the culmination of the IFRF study program for low NO_x burner development. Previous work has centred on evaluation performance in relation to air flow parameters, injector position, coal particle sizing and coal characteristics. Burner zone analyses have been made on a multitude of conditions. These tests have successfully identified the optimum design and operation for the reduction of NO_x, particularly when firing medium volatile coals in the IFRF 2.5 MW_t test burner. The present study endeavours to select and qualify guidelines which will assure that burners built on the AASB design, but an order of magnitude larger, will achieve equal or better performances.

This is an ambitious undertaking. Reference is made to earlier success by Steinmuller GmbH in scaling-up the EASB design to commercial sizes of 30 to 68 MW_t. Prototype results were better than those achieved by the test model. However, there are certain implications that the similitude maintained in the scale multiplications were more-or-less fortuitous. This study attempts to reduce the uncertainty inherent in scale projection by undertaking analyses on burners from 1.0 to 4.0 MW_t, and from these results, prescribing design criteria to ensure predictable performances in the 30 to 60 MW_t range. Even on a logarithmic scale, the degree of extrapolation appears to be excessive.

This is confirmed by the staged flame results, in which the level of NO_x production shows a slight inconsistency over the burner size range from 0.9 to 3.4 MW_t.

The report contains an excellent discussion of the several thermal and fluid mechanics techniques for scaling of burner designs. The effects on the size and location of the IRZ are particularly relevant to the AASB performance. The authors refer to another work in which the IRZ mean reverse-flow velocity is reported to be approximately 10 m/s for the Type II flame. Using coal particle size and momentum calculations, they proceed to develop the minimum particle size capable of penetrating the IRZ for each size of burner tested. Unfortunately, the initial primary jet velocity used for this development does not appear to be stated. However the results of this aspect would seem to have important implications regarding optimum pulverized coal sizing for NO_x reduction enhancement.

The final conclusion, that the aerodynamically air staged burner can be confidently scaled up while maintaining predictable NO_x level performance, seems to be well substantiated by the study data and analysis.

3.0 REPORT NO. 8

COMPUTATIONS OF NEAR BURNER ZONE PROPERTIES OF SWIRLING PULVERIZED COAL FLAMES
Report on the MMF 2 Investigation

This summary was prepared by Mr. M. LoPresti, P.Eng., of Nova Scotia Power Corporation.

1.0 OVERVIEW

This report describes the latest phase of a programme to develop a mathematical model to predict characteristics of swirling pulverized coal flame. This is part of a larger programme initiated by the International Energy Agency. The larger programme includes; design of low NO_x burners, coal characterisation studies, and use of calcium based sorbents for SO_2 removal. NO_x reduction by fuel staging was also studied. Two low NO_x pulverized coal burners have been developed.

This phase of the mathematical modelling programme (MMF2) builds on previous work and was intended to refine the quality of predictions and test the sensitivity to various parameters. Detailed data on the characteristics of various flames was available from experiments from other programmes, so the accuracy of prediction could be confirmed.

Recently, two other researchers in flame modelling have published papers on their work. The furnaces were 0.6 m and 0.8 m in diameter with lengths of 3.0 m and 3.9 m. Heat inputs were 200 KW_t and 300 KW_t. Their results are briefly mentioned and the researchers of the larger furnace are reported to conclude that "the gross features of all test flames were well predicted". (p.4).

2.0 FLAME DESCRIPTION

The predicted flames were all produced in IFRF Furnace No. 1. The furnace is refractory lined with an internal dimension of 2 m x 2 m and length 6.25 m. The heat input was 2.5 MWt. The burner was the low NO_x aero-dynamically air staged burner (AASB). Three flames were computed: one using Scotts Branch (US) coal with the injector tip positioned at the beginning of the quarl expansion; two using Coal Valley coal, one with the injector tip at the quarl edge, one with the injector tip inserted 9 cm. Both coals are high volatile bituminous but have different chemical compositions.

3.0 MATHEMATICAL MODEL

The mathematical model is composed of a numerical algorithm called QUICK (Quadratic Unstream-weighted Interpolation for Convective Kinematics) used to solve the transport equations. A model of turbulence called ASM (Algebraic Stress Model) is used to predict fluid flow, a coal devolatilization submodel, and a char combustion

submodel. The last two submodels are used to predict the rate of production of volatiles and the rate of combustion of char. Before the model can be used, it is necessary to assign a large number of parameters such as: constants for turbulence modelling; radiation constants; gas properties and their variation with temperature; and detailed coal properties.

The model requires thousands of iterations in order to achieve a solution which predicts the flame characteristics. Experience with the model has led to the establishment of several guidelines regarding indications of when a solution is in fact reached, allowable rates of change of variables, and the order of solution of variables. Several weeks of computer time are required to compute a flame.

4.0 PREDICTION OF SCOTTS BRANCH COAL FLAME

The model provided predictions of flow pattern, temperature profiles, particle trajectories, and gas concentration profiles. The area of maximum temperature was predicted to be in the boundary between the internal recirculation zone (IRZ) and main forward flow where the combustion intensity is maximum. The gas concentration profiles predict volatiles to be concentrated in the IRZ were oxygen concentration is low. Carbon monoxide concentration is highest in the boundary between the IRZ and main flow. It is deduced that mixing of volatiles and combustion air occurs in this relatively small boundary area. Inside the IRZ, concentration shows little variation. Combustion rate is determined by the rate of diffusion of oxygen into the IRZ.

The predictions were verified by comparing them to measured properties at various locations in the flame. The predicted flame temperatures near the burner were within $50^{o}K$ to $100^{o}K$ of measured temperatures, with the predicted temperatures being higher. This is reported to be very good agreement and is much better than the $400^{o}K$ to $500^{o}K$ differences from a previous modelling effort of the same flame. The concentration of O_2 was well predicted with concentration inside the IRZ slightly under-predicted. The predicted concentration of CO agreed well with the measured concentrations in the boundary between the IRZ and main flow.

5.0 SENSITIVITY OF SCOTTS BRANCH COAL FLAME PREDICTIONS TO CHOICE OF SUBMODELS AND MODEL PARAMETERS

The predictions using the ASM turbulence model were compared to predictions using another model called K-E. The predictions using the ASM model agreed more closely with the measured values. The affect of removing a random component to particle velocities was tested and it was found to not alter the overall characteristics of the flame but did adversely affect the stability of the numerical solution procedure. The affect of two assumed constants in the volatile combustion model was tested by changing them by $\pm$ 50% and was found to be minor. Another constant, used in the transport

equations, was varied from the commonly assumed 0.7 to 0.9. This caused the maximum temperature to be reduced by approximately 100°K and the combustion zone to increase slightly.

The volatile yield was varied to observe its affect on the predicted flame. The maximum predicted temperature did not change but the size on the high temperature zone and the O_2 lean area became smaller, with reduced volatile yield. Changing the devolatilization rate from a finite value to infinity did not cause significant changes in predicted flame characteristics. Char combustion rate and char reactivity were also varied but predicted flame characteristics in the near burner zone changed only slightly.

6.0 PREDICTIONS OF COAL VALLEY COAL FLAMES

These predictions were made to further validate the model and to determine whether changes in NO_x production could be predicted. The two flames differed only in the position of the injector tip; the flame designated Flame 3 had the tip at the quarl edge; Flame 4 had the tip 90 mm inside the quarl edge and was measured to produce significantly reduced NO_x. The model used for the Scotts Branch Flame was used with changes to the devolatilisation and char combustion submodels to take into account differences in properties.

In general, the model seemed to reflect observed differences in flame pattern. The flame properties predicted in the near burner zone and furnace agreed well with measurements. However predictions in the quarl zone (burner quarl and 0.5 m diameter section of furnace), where a substantial portion on NO_x is formed, were not as accurate. The model predicted lower O_2 levels and higher temperatures than were measured. It is believed that rate of volatile matter combustion inside the IRZ was not predicted. The constants used in calculating this combustion rate may be accurate enough for the larger portions of the flame but not exact enough for the detailed quarl zone measurements.

Adjustment of the constants and a refinement on the method of calculation of CD production produced a model which gave predictions which generally agreed well with measurements. The model accurately predicted the near burner zone chemistry of the two flames (low and high NO_x).

7.0 REPORT CONCLUSIONS

For the Scotts Branch coal flame, the in-flame temperature was predicted within 50°K to 100°K and the gas composition was within 2-3 percent. This is reported to be good agreement.

For the Coal Valley coal flames agreement is also considered very good except that the initial model showed large errors in O_2 concentration inside the burner quarl. The model was modified and the quality of the predictions was improved.

It was found that the use of the QUICK numerical scheme and the ASM turbulence model improved the quality of the predictions.

The modeling required data on the devolatilisation rate and high temperature volatile yield of the coals. The second is reported to be the most important property for correct prediction.

8.0 COMMENTARY

This model appears to have very good potential to accurately predict the properties of flames, such as:

1. Flame shape, length and flow pattern.

2. Flow in the burner zone.

3. Gas temperature.

4. O_2, CO and CO_2 concentrations.

The correlation obtained so far between predicted and measured properties is very promising but this is for only three flames using only two coals. More work should be done validating the model and further refining its capabilities. The validation work has only been with the one burner/ furnace arrangement in two configurations. The affects and different burners would be of interest so that for example, burner designers could predict what the results of changes in geometry would be.

It appears the model does not directly predict the concentration of NO_x. It indicates the changes in other properties which accompany changes in NO_x production. Perhaps work should be done to enable it to directly predict NO_x production.

As indicated in the report, the direct release of CO from coal is neglected and requires further investigation.

4.0 POTENTIAL COMMERCIAL DEVELOPMENT

4.1 General

Two major boiler manufacturers were approached to determine their interest in the potential commercial development of the AASB. These were Babcock & Wilcox Canada, Cambridge, Ontario and Combustion Engineering, Ottawa, Ontario. A brief review was made of the IFRF research program, and the relevant AASB performance achievements. Both manufacturers confirmed the expectation of a substantial retrofit burner market. Unfortunately, Combustion Engineering was unable to offer a detailed response because their utility applications engineering department is now located in Windsor, Connecticut, which was considered to be in potential violation of the CEA confidentiality agreement.

Babcock & Wilcox Canada Ltd. has participated to some degree in IFRF research programs in other areas, and was aware of the low-NO_x burner. They, also, have developed a Low-NO_x burner based on the air staging principle, and report typically achievable limits as:

Natural Gas Fuel	74 ppm NO_x
Fuel Oil	200 ppm NO_x
Pulverized Coal	280-290 ppm NO_x

Performance guarantees generally exceed these levels by a small margin. Their dual register burner is presently in service at the Ontario Hydro, Aticokan GS, where it is reported to release 250-300 ppm NO_x on lignite fuel. In addition to the dual register burner, Babcock & Wilcox have developed the Type XCL staged burner, which employs two concentric streams of combustion air in addition to the primary air flow.

There is an understandable reluctance on the part of Babcock & Wilcox Canada to undertake commercialization of another specialty burner in view of the availability of their own designs. However, if funding was available for the development and testing phase, Babcock & Wilcox would probably consider a licencing arrangement. It is expected that a test burner in the range of 100 to 150×10^6 Btu/h would be required to generate the performance data needed for this purpose. The development program would probably span at least two years, and the costs involved are roughly estimated to be $300,000 to $500,000.

4.2 Potential Manufacturer's Problem Areas

4.2.1 Coal Injector Axial Movement

From the IFRF reports, it is not clear to what extent axial adjustment of the fuel gun position would be required for the prototype version of the AASB. Certainly, if the capability of adjustment were deemed to be necessary, then flexible coal connection piping would be required. P.F. piping erosion has been a troublesome area in experience

gained to date. Fixed elbows and transition pieces are particularly vulnerable. A flexible expansion joint at the burner inlet would certainly be a major liability. Also, sealing of the movable coal gun at the various windbox partition plates is expected to be difficult.

4.2.2 Single Fuel Capability

According to Babcock & Wilcox, many public utility steam generator specifications in recent years have stressed dual fuel firing capability. The development of the AASB has been based entirely on performance with pulverized coal operation. This is seen as potentially detrimental to the possible future marketing of the design.

4.2.3 Carbon Burnout

Low NO_x burners have been characteristically poor performers in the area of carbon losses. It was the opinion of the Babcock & Wilcox representative that this is a generic problem that must be rectified at the full scale operating level before the product will be acceptable to public utilities. In this sense, reference to the very good IFRF Furnace No.1 burnout levels was not considered sufficient verification.

4.2.4 Substantial Improvement

The opinion was expressed that to compete with burner designs which are commercially available at present, the AASB would have to offer a substantial improvement in NO_x emission levels and/or performance flexibility. Although performance data was not subjected to a detailed evaluation, the optimum NO_x levels recorded appeared to be generally similar to those achieved by fully developed burners.

4.3 Assessment of Manufacturer's Response

Although the potential low NO_x burner retrofit market is recognized, the manufacturers contacted expressed predictable skepticism regarding the possible introduction of another burner design to the market place. It should be emphasized that the simplified arrangement drawings included in the reference reports did not permit a detailed evaluation of the AASB from the potential manufacturing aspect.

A perceived obstacle presented was the need to have the AASB demonstrate a substantial performance improvement over the capabilities of existing burners. In fact, this may be less imposing than anticipated. A very cursory survey of the current NO_x emission levels in a few selected utilities suggested that in-service experience with existing burner designs is about twice the 320 ppm (0% O_2) rate achieved by the AASB test unit.

A second anticipated source of concern was the level of complexity of the AASB design. However, comparison with existing full-scale multi-staged burners tends to emphasize the opposite relationship. As previously mentioned, detailed AASB drawings are not available and additional mechanisms will certainly evolve as the design progresses to the prototype stage. However, in basic principle, the AASB is no more intricate than present air staged burner designs.

Concern about the desirability of dual fuel capability, while certainly appropriate to new construction, would probably be less relevant to the retrofit market for which the AASB is appropriate.

In conclusion, the very preliminary discussions with selected manufacturers revealed no significant technical impediment to the development of a prototype version of the AASB.

5.0 CONCLUSIONS

5.1 General

The research work performed at the IFRF on the development of the low NO_x burner is to be commended. The results of the three year program contain much detailed analysis which is applicable to the understanding of the NO_x formation process in existing burners, and should also be of benefit in the development of future burner designs. Both the air staged precombustor and aerodynamically air staged burners were tested over a wide range and combination of operating parameters. They demonstrated the ability to burn high volatile coals with low NO_x formation. Both the AASB and ASPB achieved 320 ppm NO_x or better under optimum conditions.

5.2 Reference Reports

This review is based essentially on eight research reports, and some shortcomings of these reports must be recorded. The absence of definitions of certain design criteria, occasional omission of explanations of symbols and frequent blending of observations, conclusions and commentary made several of the reports difficult to follow. The lack of cohesion between successive reports is, perhaps, understandable in view of the several contributing authors. The overall picture created is not uncommon in research endeavors; that little time remained after completion of the testing and analysis for the presentation and explanation of results.

5.3 Precombustor Burner

The ASPB has shown some encouraging results which, as an isolated development, would justify further work. In must be recognized, however, that the Rockwell Burner, which is another CEA project, is similar in principle. It would be expensive to continue to develop two parallel technologies. Furthermore, the ASPB offers a less convenient retrofit installation than the AASB. Further evaluation by the CEA of this IFRF burner does not appear to be warranted.

5.4 Aerodynamically Air Staged Burner

Substantial NO_x reductions were achieved by the AASB, particularly on medium to high volatile coals. Test results in the range of 320 ppm (corrected to 0% O_2) were consistently recorded. In spite of industry sources' claims to the contrary, the performance of this burner appears to exceed present commercially available units. It also offers advantages in simplicity of design and moderate space requirements. However, the latter must be quantified by scale-up performance modelling.

Carbon burnout was unacceptably low in early tests (94%-98%). However, later tests under smaller ranges of variables, recorded carbon burnouts of 98% to 99.5%. An analysis of furnace parameters

(Report #3) indicated that channelling in the test furnace gas path probably accounts for the earlier high carbon losses.

5.5 Applicable Fuels

Most Canadian coals, particularly those in Nova Scotia and Alberta, are similar in characteristics to the test fuels which gave the greatest improvement in NO_x emissions during the tests. It can therefore be expected that the AASB will provide similar performance improvements when burning these coals.

5.6 Further Pilot Scale Testing

Pilot-scale testing to date has provided a substantial array of data, which has successfully:

- established the performance attainable with the AASB, and
- verified the existence of the fluid mechanics and reaction mechanisms upon which the design is based.
- indicated that a full-scale prototype should afford equal or better results than the test burner.

With these achievements, further testing at the pilot scale of 2.5 MW_t does not appear to be necessary for the development of the burner design in its present form.

5.7 Scaling-Up

As described in Report #7, indications are that the AASB can be scaled up with reasonable confidence that NO_x levels and other combustion performance characteristics will be in line with the pilot scale test results.

5.8 Burner Turn-Down

To some extent, obtaining uniform combustion performance at part load is a problem common to most pulverized fuel fired burners. However, the critical velocity and momentum relationships in the AASB will probably render it particularly susceptible to a decrease in performance in off-peak operation. It is somewhat surprising, therefore, that less than one page was expended on this topic in the total collection of reports. It is quite likely that facilities at the IFRF do not make load adjustment convenient, and certainly, stable part-load operation may be difficult to achieve on a small burner. Nevertheless, some comment on the proposed method of combustion air control and fuel flow adjustment would seem to be appropriate.

5.9 Prototype Development

Initial contacts with principal burner manufacturers suggest that external financing of the design and development costs would be a prerequisite to any commitment toward a full-scale test installation.

If funding was to be made available, a licencing arrangement could probably be made. Based on the simplified arrangement drawings contained in the reports, no significant technical obstacle was identified which would prohibit the manufacture or assembly of a full-scale version of the AASB. However, Industry reaction to the introduction of a new low-NO_x burner was predictably reserved.

5.10 Development Requirements

Prior to consideration of funding for the development of a prototype burner, the installation and operating requirements of a test facility will have to be addressed. Primarily, this would be a candidate utility willing to undertake the necessary unit modification and test program for several Canadian coals. The preferred site would likely be a unit in the 20 - 60 MW range, which could be operated with maximum flexibility regarding the system load demand.

5.11 Mathematical Modelling

Mathematical modelling has been an integral part of the development of the low NO_x burner. The model data for the near-field characterization is now better understood, and shows good correlation with experimental results. It may be appropriate to continue this modelling if the results are accepted as applicable to the scale-up dimensional criteria of the prototype builder.